MIT Technology Review

SPECIAL ISSUE!

TEN BREAKTHROUGH TECHNOLOGIES

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Tonight's forecast, mostly sunny.

From the Editor

GUIDO VITTI

Every year, *MIT Technology Review* picks the 10 technologies we think most likely to change the world.

(This year, for the first time, we are calling them "10 breakthrough technologies" instead of "emerging technologies." Why? "Emerging" has a specific meaning inside the academy and the start-ups that spin out of universities; but the adjective is a kind of jargon, and the word didn't mean much to most of our readers. "Breakthrough" seemed clearer and more accurate.)

How do we choose the 10 technologies? We want them to reflect the full range of our interests, which uniquely amongst technology media companies encompass every domain: information technology, communications, energy, biomedicine, materials, and so on. But, even more, we are interested (like our owner, MIT) in how technologies can solve really hard problems. We look first for difficulty: we select problems whose intractability is a source of frustration, grief, or comedy and whose solution will expand human possibilities. The breakthroughs are variously mature. Although we insist that every technology possess some plausible path to widespread use, some are still in the lab, some are in commercial development, and others are being sold by companies.

Unlike our annual list of 35 young innovators under the age of 35, the list of 10 breakthrough technologies is entirely subjective. There is no nomination process, nor panels of distinguished judges. The 10 technologies are an expression of our preferences and emphases, and they grow out of our reporting over the previous year. This is the stuff we like.

A good (if very early) example of the kind of technology we like is the work of Theodore Berger, whose "memory implants" are described by contributing editor Jon Cohen on page 62. Berger, who is a biomedical engineer and neuroscientist at the University of Southern California in Los Angeles, wants to restore the ability to create long-term memories in patients with severe memory problems by putting silicon chips inside their heads.

Cohen writes, "In people whose brains have suffered damage from Alzheimer's, stroke, or injury, disrupted neuronal networks often prevent long-term memories from forming. For more than two decades, Berger has designed silicon chips to mimic the signal processing that those neurons do when they're functioning properly—the work that allows us to recall experiences and knowledge for more than a minute."

Berger has not yet conducted human trials of his neuronal prostheses (the bar to test truly novel brain technologies on humans is rightly high), but his recent experiments have shown that silicon chips connected to rat and monkey brains by electrodes can process information just like actual neurons. "We're not putting individual memories back into the brain," he says. "We're putting in the capacity to generate memories."

We like Berger's technology not only because it is a technical breakthrough of the highest order, which could restore patients with a crippling debility to their full selves, but also because it could change our conception of what it means to be human. A little speculation suggests that memory implants might one day make a person more memorious than she was by nature, or preserve her plasticity late into life (so that, as an old woman, she could learn new languages or skills with the ease of toddler), or provide yet more science-fictional capabilities.

But write to jason.pontin@technologyreview.com and tell me what you think of this year's 10 breakthrough technologies.

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MAY/JUNE 2013

10 Breakthrough Technologies 2013

Think of the most frustrating, intractable, or simply annoying problems you can imagine. Now think about what technology is doing to fix them. That's what we did in coming up with our annual list of 10 Breakthrough Technologies. We're looking for technologies that we believe will expand the scope of human possibilities.

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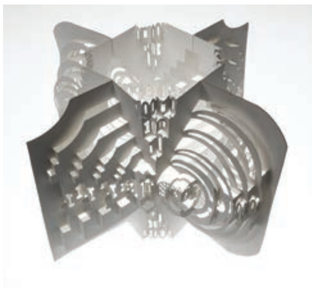

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Paper sculpture by Ingrid Siliakus for *MIT Technology Review*

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De Technologia non multum scimus. Scimus autem, quid nobis placeat.

Feedback

5 Most Discussed Stories

MIT Technology Review Volume 116, Number 2

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Intentionally engineering Earth's atmosphere to offset rising temperatures could be far more doable than you imagine, says David Keith. But is it a good idea?

A Cheap and Easy Plan to Stop Global Warming

By David Rotman

Here is the plan. Customize several Gulfstream business jets with military engines and with equipment to produce and disperse fine droplets of sulfuric acid. Fly the jets up around 20 kilometers—significantly higher than the cruising altitude for a commercial jetliner but still well within their range. At that altitude in the tropics, the aircraft are in the lower stratosphere. The planes spray the sulfuric acid, carefully controlling the rate of its release. The sulfur combines with water vapor to form sulfate aerosols, fine particles less than a micrometer in diameter. These get swept upward by natural wind patterns and are dispersed over the globe, including the poles. Once spread across the stratosphere, the aerosols will reflect about 1 percent of the sunlight hitting Earth back into space. Increasing what scientists call the planet's albedo, or reflective power, will partially offset the warming effects caused by rising levels of greenhouse gases.

The author of this so-called geoengineering scheme, David Keith, doesn't want to implement it anytime soon, if ever. Much more research is needed to determine whether injecting sulfur into the stratosphere would have dangerous consequences such as disrupting precipitation patterns or further eating away the ozone layer that protects us from damaging ultraviolet radiation. Even thornier, in some ways, are the ethical and governance issues that surround geoengineering—questions about who should be allowed to do what and when. Still, Keith, a professor

Illustrations by Grafilu

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A Cheap and Easy Plan to Stop Global Warming

We're already unintentionally engineering our atmosphere with greenhouse gases. If we feel uncomfortable about geoengineering, shouldn't we feel uncomfortable about using the car every day? **–JosyH**

With the money this project would swallow, you could replant huge patches of land. Or you could change the culture that created the problems in the first place. But that would take courage, time, and creativity—unlike this "quick fix" of spraying more stuff in the atmosphere, while down below, nothing changes. **–antalandtica**

Free Speech in the Era of Its Technological Amplification

Speech has always come at a cost. It may be so simple as someone taking you out to the woodshed if you get too mouthy, or it may be cost to your reputation or your employability when others view you with skepticism. Legal or not, moral or not, like it or not, there have always been controls on speech. If you go too far there is a consequence. It seems unrealistic that what applies throughout life will not apply to the Internet. **–John May**

Windows 8: Design over Usability

What a schizophrenic article! But it befits a schizophrenic operating system. Businesses will inevitably push Microsoft to do something to make it more usable, and Microsoft will do it, or risk losing them to Linux. Legacy programs are rampant in the business world, like it or not. And not all of them can be rewritten at the drop of an operating system. I hear of a lot of frustration and anger from business acquaintances who bought Windows 8 computers and can't do anything with them. It seems to be the dirty little secret that doesn't make it into these articles. **–krm1255**

50 Disruptive Companies: Ambri

Interesting claims, cool science, but an economic disaster. If the cells only achieve a finite lifetime of 5,000 cycles, then the addition of 10 cents per kilowatt-hour to the cost makes it a nonstarter. **–ctyankee**

The devil is always in the details for rechargeable batteries, as Boeing has found out. My guess is making the cells workable in the lab will require less man-hours than all the "systems design" to make them plug and play. **–Bonobo**

50 Disruptive Companies: BGI-Shenzhen

BGI-Shenzhen's sequencing-for-hire scheme will enable China to acquire massive amounts of valuable intelligence. Any university or drug company that outsources its sequencing projects will be informing the Chinese of its research goals. The Chinese will then be free to exploit those resources, which they were paid to receive, in any manner desired. It is a brilliant and extremely cost-effective way for China to advance its corporate espionage program. **–golemme**

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Letters and comments may be edited for both clarity and length.

The Advantages of Outrage

Jason Pontin has written (in "Free Speech in the Era of Its Technological Amplification," March/April) a perceptive analysis of a timeless question: what changes in law need to be adopted in order to account for technological advances? In answering that question, he takes the right approach by taking up John Stuart Mill's harm principle.

Mill's principle is both profound and incomplete. It expresses a strong antipaternalist sentiment that no government, individual, or group should be able to reform the private preferences of other individuals. That principle is a welcome recipe for social peace: if the rule were otherwise, it would be necessary to decide which individuals or groups occupied the dominant position with respect to other groups. Any interested group would find it difficult to choose on neutral principles which group should have that preferred position.

Mill does less well, however, in defining how the harm principle works. One possible interpretation of this principle is, Pontin writes, that harm should mean "physical or commercial injury" but exclude "personal, religious, or ideological offense."

Pontin's version is clearly correct insofar as it excludes "religious or ideological offense" from the category of what lawyers call "cognizable" harms. That odd term "cognizable" is meant to capture this understanding. Religious and ideological offense are in fact real harms, subjectively experienced. The willingness to cut them out of the harm principle cannot rest on a simple denial of the fact, but must rest on the awareness that for the long-term success of the system, each person must waive that claim against all others, no matter how acute the feeling. Essentially, the comprehensive judgment is that we all are better off when we have to suffer the slings and arrows of this sort of abuse than we are when these attacks are subject to extensive legal control that runs the serious risk of state censorship.

The claim, therefore, behind the offense principle is one of universal *privilege* to hurt the feelings of others; it is not a factual claim that there is no harm at all. That difference matters, because when voluntary institutions put speech codes into place for their members, they are responding to a real harm that by consent can be controlled within a limited forum, even if the state cannot dictate that same relationship among strangers. Private ordering has advantages that public ordering cannot match.

"We are all better off when we have to suffer the slings and arrows of abuse than when attacks are subject to extensive legal control."

But any effort to transport the harm principle to larger social settings gives everyone a huge incentive to become truly offended at the speech of others in order to have a lever to suppress their ideas. The angrier you get, the greater your rights. Work yourself into a white heat, and the world must yield to your outrage. That dynamic will not work in a private setting where the organizer of the group has strong incentives to prevent any systematic move to extremes.

Unfortunately, Pontin's formulation of the rule contains serious errors that stem from his willingness to accept both "physical and commercial injury." Physical harm certainly sets out a valid *prima facie* case that is subject to defenses that relate to consent and self-defense. But commercial harm is much too broad to be treated in the same fashion.

Richard Allen Epstein is a professor of law at the New York University School of Law and a professor of law emeritus and senior lecturer at the University of Chicago Law School.

Jason Pontin responds

I'm grateful that the author of *Principles of a Free Society* (1998) should take the time to read my essay. (In his valuable book, Professor Epstein discusses the harm principle and its application to modern communications.) He takes exception to my willingness to accept "commercial injury" as a kind of harm whereby free speech might justifiably be limited. I was thinking of copyright infringement, defamation, and the divulging of trade secrets. I take his point that I failed to distinguish their differences adequately. Perhaps so, for a distinguished jurist. But I was writing about how U.S. Internet companies should treat free speech on their platforms, and not the letter of the law. That all three are real harms caused by kinds of speech is scarcely controversial. Indeed, they are (in his legal jargon) "cognizable harms" in that they may all fall under the jurisdiction of the courts. In fact, they do so (albeit very differently) every day.

Perplexed about Paraguay

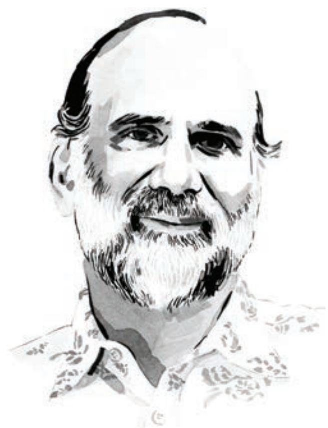
Compliments on your "50 Disruptive Companies," which I read with interest, as much for the companies excluded as for those included. One complaint, however, regarding the Upfront page on "Innovation Efficiency": really, should Paraguay of all benighted lands rank higher than North America or even its progressive neighbor, Brazil? The fact that it does is a reflection on the ridiculous parameters INSEAD uses among its measures. Royalty and license income may well flow to Paraguay, but probably because of a low tax or registration fee, not because of the inventiveness of its indigenous companies or citizens.

Andrew Viterbi, who cofounded Qualcomm, is the inventor of the Viterbi algorithm, widely used in wireless communications.

Views

Vincent Blondel

Leila Takayama



Bruce Schneier

COMMUNICATIONS

Data Sources

Mobile phones are great sources of data—but we must be careful about privacy, says Vincent Blondel.

Anyone who has worked with mobile-phone data knows how incredibly useful such information can be, even when it's anonymous. It is amazing—but at the same time frightening—what massive quantities of spatiotemporal data points from mobile phones can tell us about ourselves, our lives, and our society in general.

Mobile phones know where we are and when, and whom we talk to. In some cases they even know when and in what amounts we add credit to prepaid phones, which in some places is a good proxy for how much money people have. All this data can be harnessed for the public good (see "Big Data from Cheap Phones," page 50). In countries where even population estimates are hard to get, mobile phones constitute a unique source of information.

Recently, the telecom operator Orange challenged researchers around the world to analyze "anonymized" mobile-phone data sets from Ivory Coast and see how the information might be used. The data sets are based on more than two billion records of communications between five million customers in the African country.

This "data for development" challenge—the first of its kind—has been received with tremendous enthusiasm. Over the last six months, hundreds of researchers have proposed ideas that are creative, original, and useful. Among many others, they suggest ways to respond to emergencies, improve health, optimize transportation infrastructures, monitor development policies, prevent violence, and anticipate the spread of diseases such as meningitis, malaria, or cholera.

Unfortunately, without proper care these kinds of data sets can be misused, and making the information available could compromise people's privacy. A few data points suffice to identify most customers, even if their names are stripped from records. But at the same time, those data points may save their lives, or at least help make those lives better and safer. These trade-offs should be worked out and debated so that we can benefit from data in a way that respects the interests of all.

Vincent Blondel is a professor of applied mathematics at the University of Lovain in Belgium and a research affiliate with the Laboratory for Information and Decision Systems at MIT.

ROBOTICS

Friendly Machines

Making human-friendly robots is a pressing challenge and a big opportunity, says Leila Takayama.

As a research scientist studying human-robot interaction, I hear this question all the time: when are your robots going to replace me? But that is certainly not my goal.

A more important objective, to my mind, is making robots more human-friendly in their form, behavior, and function. By this I mean that robots should be appealing and approachable. They should behave in ways that are easy for humans to interpret, and they should perform functions that meet human needs. This applies in places like factories where more robots can work effectively alongside people (see "Baxter: The Blue-Collar Robot," page 38).

This is not about making human-like robots. Humanoid robots have a place in

SAM KERR

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entertainment, medical training, and possibly other domains, but human-friendly robots are not necessarily humanoid. In fact, by setting user expectations too high, looking too human could make it more difficult for a robot to interact with people. We are often disappointed and frustrated with the limited capabilities of robots that look as if they should be just as smart as we are.

These robots also do not need to behave just like humans. They might, for example, behave more like service dogs. As long as they are predictable, robots have a hope of making it in the everyday world. Many people know how to communicate with dogs just fine without needing language at all.

Finally, these human-friendly robots must meet real human needs, not only the needs of their inventors. Fetch-a-beer and fold-a-towel demos are nice scientific steps toward building more general robotic capabilities. But what we need now is for human-centered-design researchers and product-minded entrepreneurs to do the dance of the necessary and the possible with the robotics community.

Why does this humanist stuff matter? Because it will help us realize the true potential of the technology. Too many long-term studies of robots in hospitals, offices, and homes have revealed the problem with ignoring the importance of human-to-robot interaction: the robots end up interred in closets, retired to garages, or "mysteriously" disabled and shoved under desks.

Many of my robotics colleagues cringe at the challenges presented by unstructured environments that personal robots need to navigate. But the untrained people around these robots present an entirely different set of equally important challenges. Without serious involvement from the interaction-design, product-design, and entrepreneurial communities, personal robots don't stand a chance of surviving out in the "real world."

Leila Takayama, a member of MIT Technology Review*'s Innovators Under 35 list in 2012, is a research scientist and manager at Willow Garage.*

INTERNET

Online Nationalism

The rhetoric about "cyberwar" is getting out of control, says Bruce Schneier.

For something that was supposed to ignore borders and bring the world closer, the Internet is fostering an awful lot of nationalism right now. We're seeing increased concern about where IT products and services come from: U.S. companies are worried about hardware from China, European companies are worried about cloud services in the U.S., and Russia and China might each be building their own operating systems to avoid using foreign ones.

I see this as an effect of the saber-rattling that has been going on. The major nations of the world are in a cyberwar arms race, and we're all being hurt by the collateral damage.

Our nationalist worries have recently been fueled by reports of attacks from China. These attacks aren't new—cybersecurity experts have been writing about them for at least a decade, and the most recent allegations aren't very different. This isn't to say that the Chinese attacks aren't serious; the country's espionage campaign is sophisticated. But it's not just China. All governments have discovered the Internet; everyone is spying on everyone else. China is certainly worried about the U.S. Cyber Command's recent announcement that it was expanding from 900 people to almost 5,000, and about the National Security Agency's massive new data center in Utah.

At the same time, many nations are demanding more control over the Internet within their borders. They reserve the right to spy and censor, and to limit the ability of others to do the same.

But remember: this is not cyberwar. It's espionage, something that's been going on between countries ever since countries were invented. Yet the rhetoric we're hearing is of war.

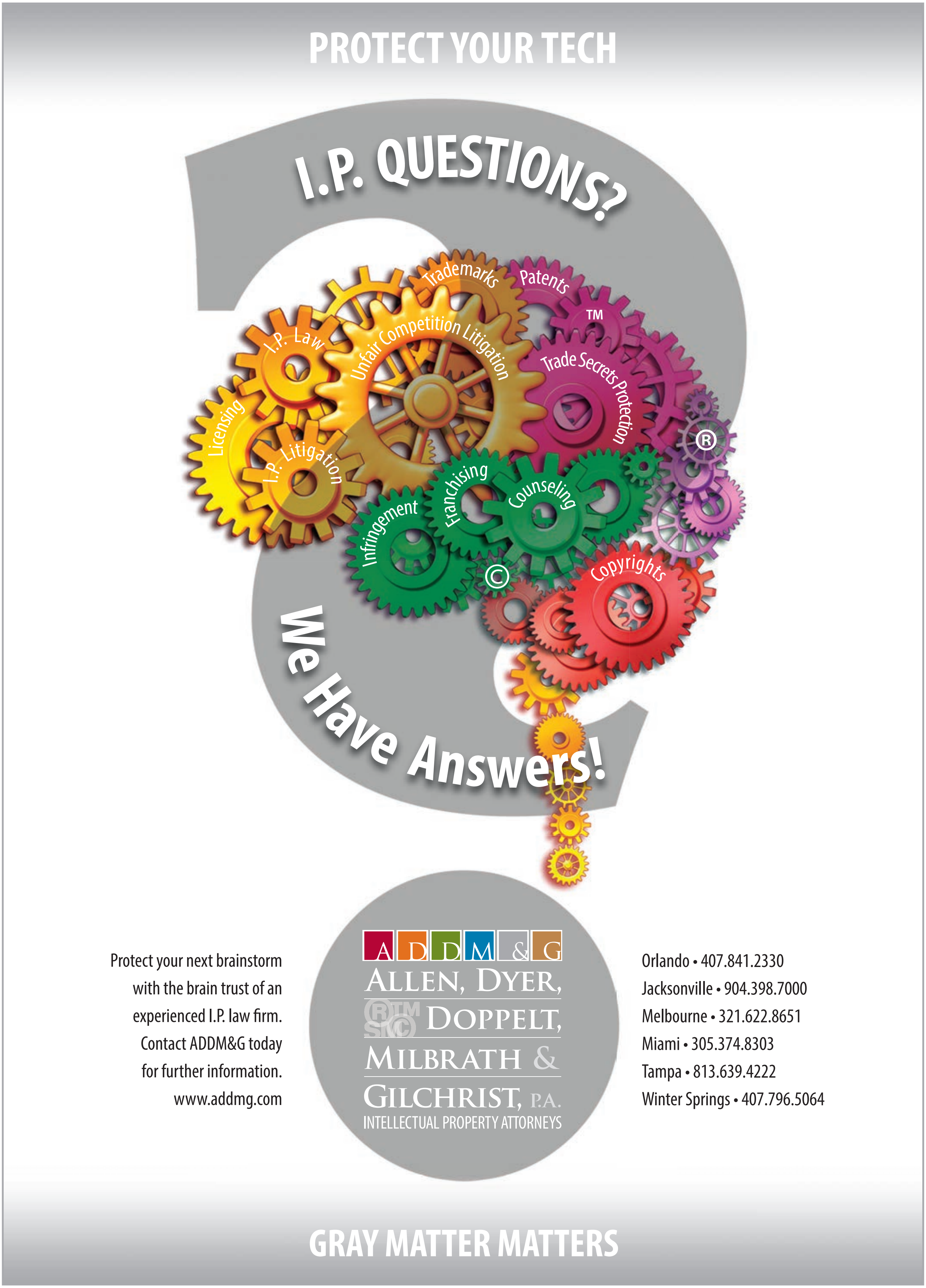
Unfortunately, that plays into the hands of the military and corporate interests that gain power and profit from the cyberwar arms race in the first place. The more we believe we are "at war," the more willing we are to give up our privacy, freedoms, and control over how the Internet is run.

Arms races are fueled by two things: ignorance and fear. We don't know the capabilities of the other side, and we fear that they are more capable than we are. So we spend more, just in case. The other side, of course, does the same. That spending will result in more cyberweapons for attack and more cybersurveillance for defense. It will result in more government control over the protocols of the Internet, and less free-market innovation in the same arena.

At worst, we might be about to enter an information-age Cold War: one with more than two "superpowers." This is inherently destabilizing. It's just too easy for this amount of antagonistic power and advanced weaponry to get used: for a mistaken attribution to be reacted to with a counterattack, for a misunderstanding to become a cause for offensive action, or for a minor skirmish to escalate into a full-fledged cyberwar.

Nationalism is rife on the Internet, and it's getting worse. We need to tamp down the rhetoric.

Bruce Schneier is chief security technology officer of BT.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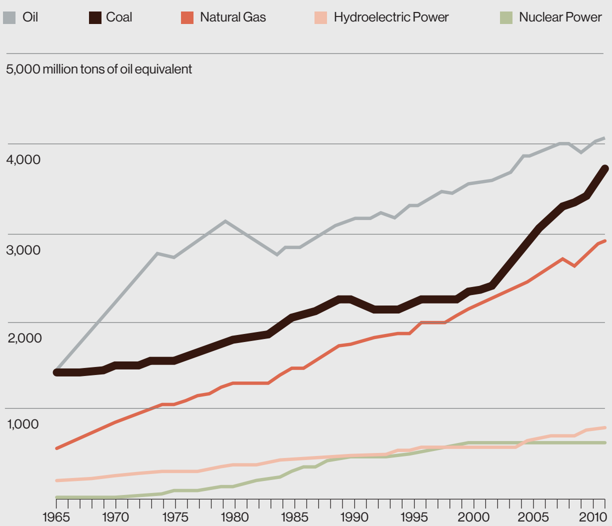
Upfront

The Enduring Technology of Coal

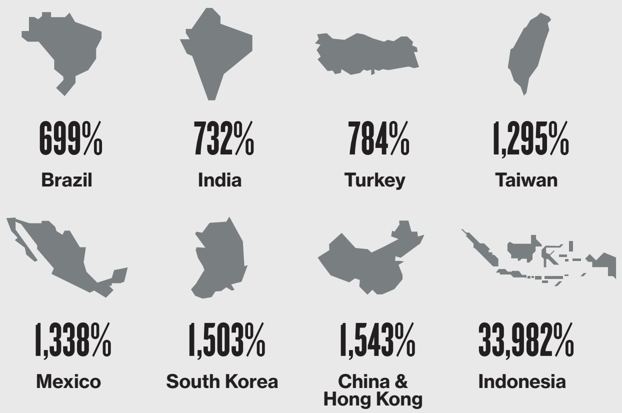
Despite the need to reduce carbon-dioxide emissions, the burning of coal has only been accelerating. Coal has been the world's largest source of electricity for well over a century, but it's now on pace to supplant oil as the top energy source overall.

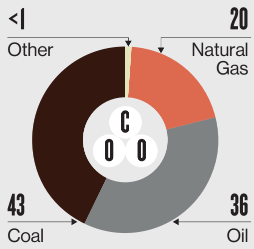


Key Ingredient in Industrialization

Use of coal has skyrocketed in countries that modernized their economies in the past 50 years.

Percentage increases from 1965 to 2011





Climate Effects

Coal accounts for the largest percentage of energy-related CO_2.

The Future of Coal

New coal plants will provide huge amounts of power.

1,199 Proposed coal plants worldwide

1,401,278 Megawatts of electricity that those plants could supply

1,050,000 Megawatts of capacity on the entire U.S. power grid in 2011

40-60 YEARS

Life span of a typical coal plant

LAURA CATTANEO; DATA FROM EIA, IEA, BP, WORLD RESOURCES INSTITUTE

Upfront

100 years: The supply of natural gas that Japan might be able to unlock from methane hydrates, frozen deposits found in ocean sediments and near permafrost.

Welcome to the Malware-Industrial Complex

The U.S. government is developing new computer weapons and driving a black market in "zero-day" bugs. The result could be a more dangerous Web for everyone.

By Tom Simonite

Every summer, computer security experts get together in Las Vegas for Black Hat and DEFCON, conferences that have earned notoriety for demonstrations of critical security holes in widely used software. But the bugs unveiled in recent years haven't been quite so dramatic.

One reason is that a freshly discovered weakness in a popular piece of software, known in the trade as a "zero-day" vulnerability because the software makers have had no time to develop a fix, can be cashed in for much more than a reputation boost and some free drinks at the bar. Information about such flaws can command hundreds of thousands of dollars from defense contractors and governments.

This trade in zero-day exploits is poorly documented, but it is part of a new industry that in the years to come is likely to swallow growing portions of the U.S. national defense budget, reshape international relations, and perhaps make the Web less safe for everyone.

Zero-day exploits are valuable because they can be used to sneak software onto a computer system without detection by conventional security measures, such as antivirus packages or firewalls. Criminals might do that to intercept credit card numbers. An intelligence agency or military force might steal diplomatic communications or shut down a power plant.

It became clear that this type of assault would define a new era in warfare in 2010, when security researchers discovered a piece of malicious software, or malware, known as Stuxnet. Now widely believed to have been a project of U.S. and Israeli intelligence, Stuxnet was designed to infect multiple systems needed to access and control industrial equipment used in Iran's nuclear program. The payload was clearly the work of a group with access to government-scale resources and intelligence, and it was made possible by four zero-day exploits for Windows that allowed it to silently infect target computers. That so many precious zero-days were used at once was just one of Stuxnet's many striking features.

Since then, more Stuxnet-like malware has been uncovered, and it's involved even more complex techniques. It is likely that even more has been deployed but escaped public notice. Meanwhile, govern-

ILLUSTRATION: DAN PAGE; ISTOCK

Upfront

ments and companies around the world have begun paying more and more for the exploits needed to make such weapons work, says Christopher Soghoian, a principal technologist at the American Civil Liberties Union.

"On the one hand the government is freaking out about cyber-security, and on the other the U.S. is participating in a global market in vulnerabilities and pushing up the prices," says Soghoian. Even civilian law-enforcement agencies pay for zero-days, he says, in order to sneak spy software onto suspects' computers or mobile phones.

Even if an attack using malware fails, copies can reach computers that weren't targeted.

Exploits for mobile operating systems are particularly valued, says Soghoian, because unlike desktop computers, mobile systems are rarely updated. Apple sends out updates to iPhone software a few times a year, meaning that a given flaw could be exploited for a long time. Sometimes the discoverer of a zero-day vulnerability receives a monthly payment as long as a flaw remains undiscovered.

No law directly regulates the sale of zero-day exploits in the United States or elsewhere, so some traders pursue it quite openly. A Thailand-based security researcher who goes by the name "the Grugq" has spoken to the press about negotiating deals worth hundreds of thousands of dollars with government buyers from the United States and Western Europe. The French security company Vupen states on its website that it "provides government-grade exploits specifically designed for the Intelligence community and national security agencies to help them achieve their offensive cyber security and lawful intercept missions." Last year, Vupen employees demonstrated a zero-day flaw that compromised Google's Chrome browser, but they turned down Google's offer of a $60,000 reward if they would share how it worked. What happened to the exploit is unknown.

No U.S. government agency has gone on the record as saying that it buys zero-days. But U.S. defense agencies and defense contractors have begun to acknowledge that they intend to launch as well as defend against cyberattacks, a stance that will require new ways to penetrate enemy computers.

Talking about offense this way could introduce an element of deterrence, an established strategy for nuclear and conventional conflicts. But as with past arms races, the competition between U.S. and overseas governments and contractors could make the world more dangerous for everyone. The ease with which perpetrators of a computer attack can hide their tracks raises the risk that such weapons will be used, says Sujeet Shenoi, who leads the U.S.-government-sponsored Cyber Corps Program at the University of Tulsa. And worse, even if an attack using malware is unsuccessful, there's a strong chance that copies will reach computer systems that weren't targeted, as Stuxnet did. Some security firms have identified criminal malware that uses methods first seen in Stuxnet.

"The parallel is dropping the atomic bomb but also leaflets with the design of it," says Peter Singer, director of the 21st Century Defense Initiative at the Brookings Institution, a Washington think tank. He estimates that around 100 countries have cyberwar units of some kind, and around 20 have formidable capabilities: "There's a lot of people playing this game."

QUOTED

"For pretty much any product sold in a big-box retail store, $10 is a magic number to get consumers to try them."

–Mike Watson, vice president of corporate marketing at Cree, maker of an efficient, general-purpose LED light bulb that can now be bought for that price.

TO MARKET

Head Safety

CheckLight

COMPANIES:
Reebok and MC10

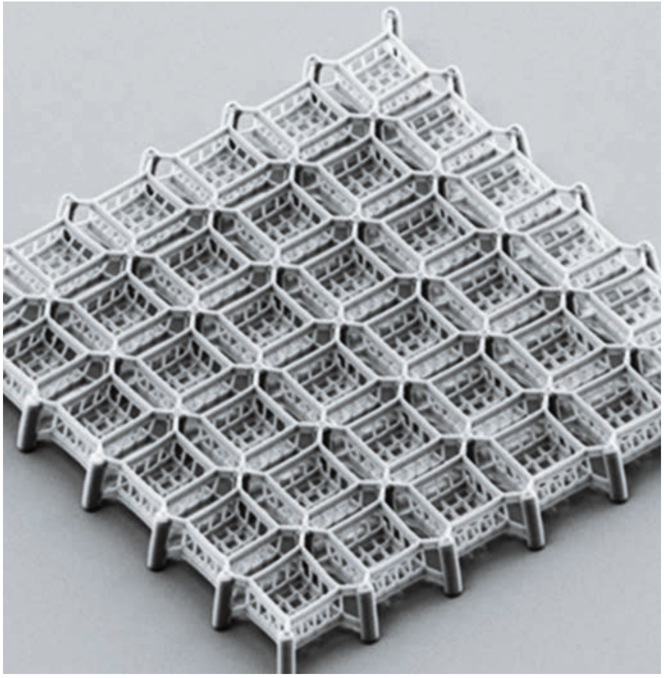
PRICE:
$150

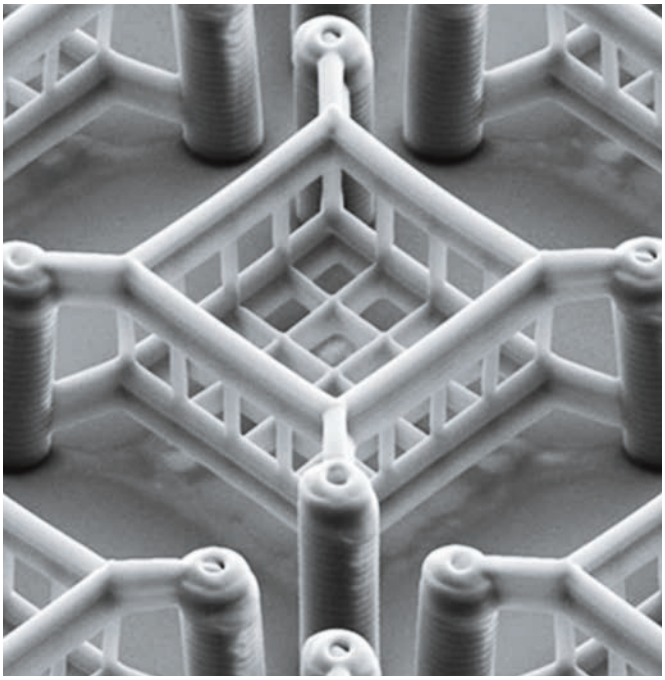
AVAILABILITY:
June

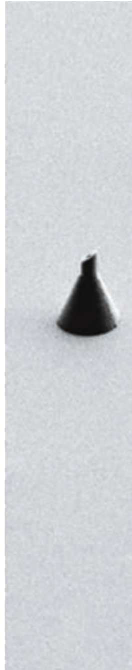
Rising fears about concus-sions in sports led to this product: a skullcap laden with sensors that can detect when an athlete has sustained a blow to the head and should come to the sidelines for an assessment. Such hits aren't always seen by coaches and trainers. A yellow light comes on after a moderate hit; a red light indicates that the hit was severe. Football helmets with sensors already exist, but they cost more and aren't widely used in youth programs. This product, which can be worn under a helmet or without one, could also be useful in hockey, soccer, and other sports where players fall or get knocked in the head.

COURTESY OF CREE; COURTESY OF MC10

Upfront







Micro 3-D Printer Creates Tiny Structures in Seconds

A faster printer could be the breakthrough needed to move the technology from research labs to the medical and electronics industries.

By Prachi Patel

Using 3-D printing to make toys, iPhone covers, and jewelry is exciting hobbyists, but much of the technology's impact could be felt at a much smaller scale. Printing tiny structures with features a few hundred nanometers in size looks like a promising way to make heart stents, microneedles for painless shots, and scaffolds for growing cells and tissue.

Now a company called Nanoscribe, a spinoff from the Karlsruhe Institute of Technology in Germany, has developed a tabletop 3-D microprinter that can create complicated microstructures 100 times faster than is possible today.

"If something took one hour to make, it now takes less than one minute," says Michael Thiel, the chief scientific officer of Nanoscribe, which plans to start selling its machine in the second half of this year.

So far, 3-D microprinting has been used only in research laboratories, because it's pretty slow. For example, in the lab of Julia Greer, a professor of materials science at Caltech, the first-generation Nanoscribe printer is used to create and study materials that could be used for catalysts and to make strong, lightweight structures. But Nanoscribe expects its faster machine to find commercial use. Thiel says medical, life sciences, and nanotechnology companies are interested. "It might have an industrial breakthrough very soon," he says.

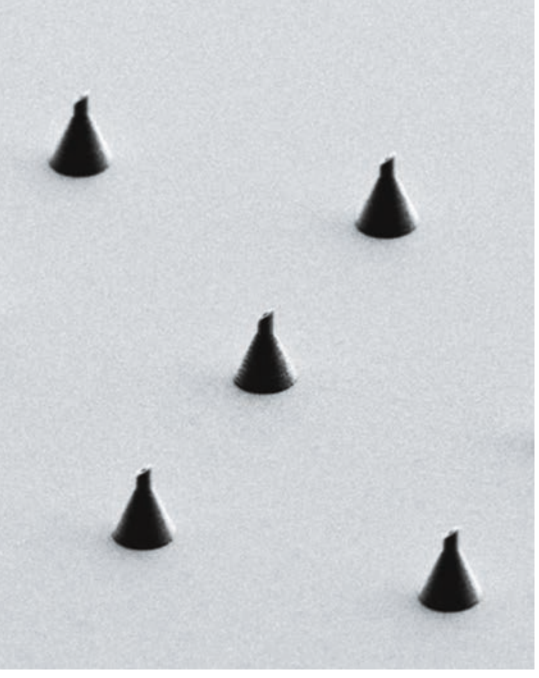
One application could be in the electronics industry, where patterning nanoscale features on chips currently involves slow, expensive techniques. The new technology would quickly and cheaply yield polymer templates that could be used to make metallic structures.

The technology behind most 3-D microprinters is called two-photon polymerization. It involves focusing tiny, ultrashort pulses from a near-infrared laser on a light-sensitive material. The material solidifies at the focused spots. As the laser beam moves in three dimensions, it creates a three-dimensional object.

Today's printers, including Nanoscribe's first-generation system, keep the laser beam fixed and move the light-

COURTESY OF F. KLEIN, B. RICHTER, J. FISCHER, T. STRIEBEL, AND M. BASTMEYER, KARLSRUHE INSTITUTE OF TECHNOLOGY

Scanning electron microscope images show a cell scaffold printed using Nanoscribe's new device (left), a detail of the scaffold (center), and an array of microneedles (right).



Electronics makers could print tiny features on chips more quickly and cheaply than is possible today.

sensitive material along three axes using mechanical stages, which slows down printing.

To speed up the process, Nanoscribe's new tool uses a tiny moving mirror to reflect the laser beam at different angles. Thiel says generating multiple light beams with a microlens array could make the process even faster in future generations of the printer.

The smallest features that can be created using the Nanoscribe printer measure about 30 nanometers, says Caltech's Greer. "This is very challenging to do, and the Nanoscribe tool excels at it," she says. "I don't think there is another company out there that is capable of such precision."

JOHN UELAND

Nanocapsules Sober Up Drunken Mice

Researchers encase alcohol-digesting enzymes in a nanoscale polymer to keep them from degrading in the body before they go to work.

By Mike Orcutt

Researchers have reduced blood alcohol levels in intoxicated mice by injecting them with nanocapsules containing enzymes that are instrumental in alcohol metabolism. The treatment demonstrates a novel drug delivery technology that could have broad medical applications.

Enzymes are proteins that catalyze a wide range of biological processes in the body, making them attractive candidates as therapeutics. Many important biological functions require precisely arranged groups of different enzymes working in concert, often inside a cellular subcomponent called an organelle. Though researchers have tried for years to develop such complexes in the lab, it has proved extremely difficult to maintain stable proteins and precisely control their size and arrangement.

The new research, which was described in the journal *Nature Nanotechnology*, involves packaging multiple enzymes inside a nanoscale shell. The resulting functional enzyme complex, made of a nontoxic polymer, "almost mimics an organelle," says Yunfeng Lu, a professor of chemical and biomolecular engineering at the University of California, Los Angeles, who led the research with Cheng Ji, a professor of biochemical and molecular biology at the University of Southern California. The capsule stabilizes the enzymes and protects them against degrading in the body.

To demonstrate the delivery method, the researchers injected the mice with capsules containing two enzymes. One of them, oxidase, produces hydrogen peroxide, so it has to work in concert with another enzyme that decomposes this potentially harmful by-product. The researchers report that the mice receiving the enzyme treatment saw their blood alcohol content fall quickly and significantly compared with mice in a control group.

The advance could open the door to an alcohol prophylactic or antidote that could be taken orally, Lu says. Since alcohol metabolism naturally occurs in the liver, it would "almost be like having millions of liver cell units inside your stomach or in your intestine, helping you to digest alcohol," he says.

This enzyme-delivery method could have much wider applications as well. Indeed, these researchers are developing other drugs based on the nanoscale encapsulation process; they are working with the pharmaceutical company Kythera on a hair-loss prevention drug that would rely on nanocapsules to deliver—through the skin—an enzyme that breaks down dihydrotestosterone. Also known as DHT, it is a hormone that causes male pattern baldness.

Upfront

QUOTED

"I didn't believe it at first, but we dug deeper into it and realized it was real—people were taking a lot of pictures of Starbucks mugs."

–Deobrat Singh, cofounder of gazeMetrix, a startup that helps advertisers detect when their customers have posted photos on social-media sites.

Adaptive Microchips Could Make Electronics Tougher

An integrated circuit that can withstand blasts from a laser shows a way to make ordinary chips more efficient and reliable.

By Katherine Bourzac

Caltech researchers have demonstrated a complex integrated circuit that survives substantial damage by reconfiguring the way it processes information.

The chip does not physically repair flaws; it uses a second processor to come up with new ways to perform a task in spite of the damage. The chip can also be programmed to prioritize energy savings or speed. Ali Hajimiri, the Caltech professor of electrical engineering who led the work, says chips that tune their own performance on the fly could also perform better under ordinary circumstances.

Self-healing circuits could be resilient to manufacturing flaws, and they could withstand damage caused by high temperatures or the deterioration that comes with aging. That could lead to more robust military communication equipment and consumer electronics alike.

Hajimiri's group is the first to demonstrate this kind of capability in a complex integrated circuit—in this case a power amplifier, a type of circuit that processes signal transmission in cell phones and other telecommunication devices. The self-healing chip consists of 100,000 transistors, several types of sensors, and an embedded processor that monitors the circuit's performance and runs algorithms to assess how it can be improved.

In research published in *IEEE Transactions on Microwave Theory and Techniques*, the Caltech group showed that a circuit equipped with the self-healing system continued to work even after being blasted with a laser to knock out about half its transistors. It takes just tens of milliseconds to adjust to the damage. A circuit that wasn't subjected to this attack was able to consume 50 percent less power than an ordinary circuit by reconfiguring itself for maximum efficiency.

The secondary processor that makes this possible monitors the circuit by analyzing sensor data about temperature, voltage, current, power, and more. It can be programmed to optimize these parameters for a particular outcome—for example, to maximize the purity or power of the signal produced by the amplifier. The program then figures out how to change the circuit to best achieve that goal. It could change the voltage applied to particular transistors in the circuit, or alter the way signals are routed through it so as to avoid a damaged area. Hajimiri says the circuit has about 250,000 possible states.

Hajimiri says it should be possible to apply this concept to any kind of circuit. That could free chip designers from having to make sure that circuits can withstand rare events like temperature extremes, voltage fluctuations, or interference. The ability to do so usually comes at a cost of performance—a trade-off that will become increasingly important as silicon transistors are ever more aggressively miniaturized.

TO MARKET

Steadying the Hand

LiftWare spoon

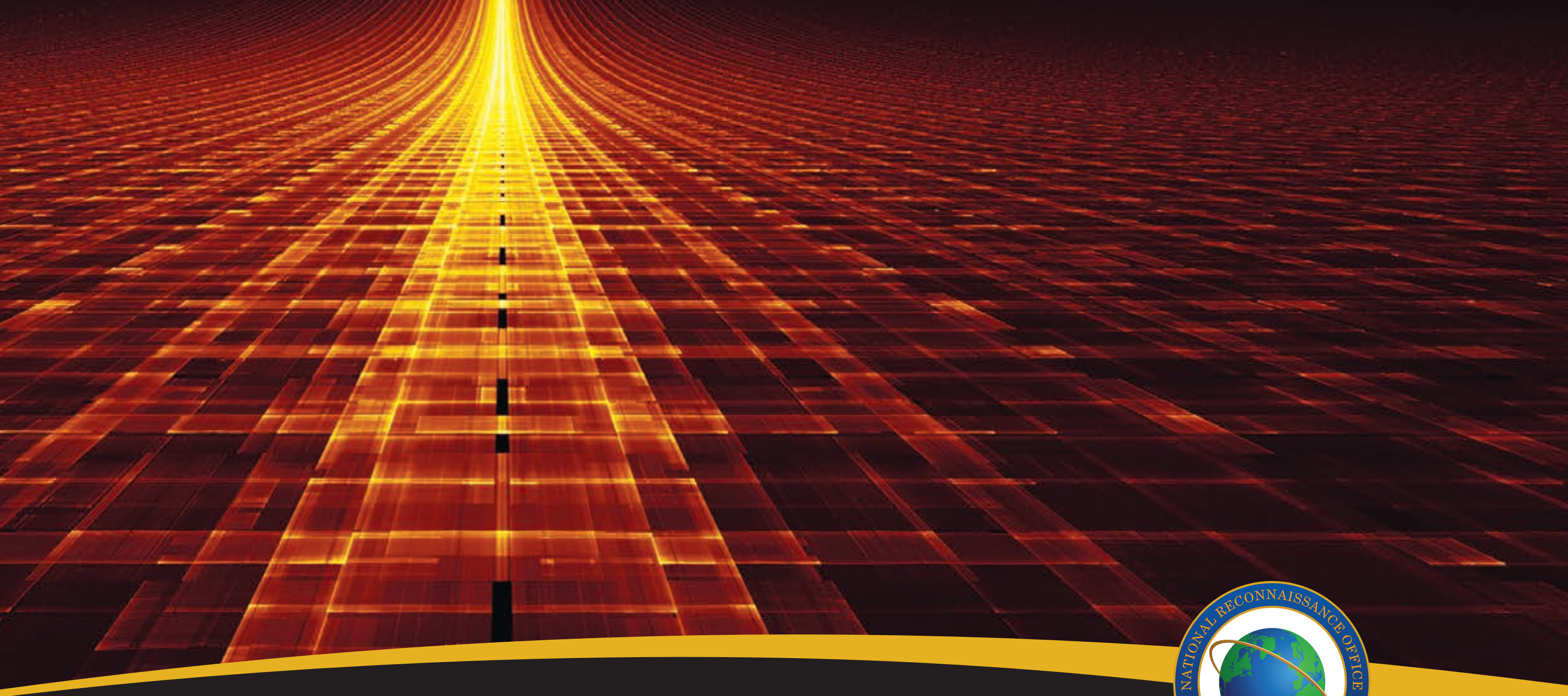
COMPANY:
Lift Labs

PRICE:
$299

AVAILABILITY:
Late summer

People with tremors caused by strokes, Parkinson's disease, or other problems could find eating much easier with a spoon that corrects for their shaking hands. Engineers at Lift Labs, a San Francisco–based company focused on health-care devices, put motion sensors in the handle of the spoon to detect the unintentional repetitive movements that characterize tremors. To counteract the tremors, motors in the handle move the bowl of the spoon in the opposite direction. The spoon doesn't completely eliminate the shaking, but it is steadied just enough to more consistently hold food. The company plans to create other utensil attachments that can plug into this spoon's rechargeable base.

COURTESY OF DEOBRAT SINGH; COURTESY OF LIFT LABS



Upfront

20,000 gallons
The amount of cellulosic ethanol, which comes from wood scraps and other plant waste, produced by commercial-scale facilities in the U.S. in 2012

500,000,000 gallons
The 2012 target for cellulosic ethanol production that was set by a 2007 law

Why More Solar Companies Should Fail

Solar manufacturers like Suntech are struggling. Hundreds need to die for the industry to recover.

By Kevin Bullis

Suntech, a Chinese company that as recently as 2011 was the world's largest producer of solar panels, has been teetering on the edge of bankruptcy. That might seem ominous for the solar market. But it's not necessarily so.

Given that the market for solar panels is flooded, hundreds of solar companies might need to shut down production if supply is to get back in line with demand. That would halt or slow the plunge in prices, which in turn could help the remaining companies justify buying new equipment and introducing the innovations that will ultimately be needed for solar power to compete with fossil fuels.

The worldwide solar glut is partly the result of big government-backed investments in factories in China, where two-thirds of solar panel production capacity is located. The surplus has been good news for consumers and installers, because it's helped drive a 60 percent drop in the price of solar panels since the beginning of 2011, according to GTM Research. Solar panels sold for $4 per watt eight years ago. Now 78 cents per watt is common, says Jenny Chase, an analyst at Bloomberg New Energy Finance.

Workers assemble solar panels at a Suntech factory in Wuxi, China. Suntech's soaring production has helped contribute to a two-year glut of panels.

But the falling prices have been hard for solar manufacturers. They have been able to lower their costs either through incremental improvements to their existing manufacturing equipment or, to a large extent, by taking advantage of decreased materials costs. But many manufacturers haven't been able to cut expenses fast enough to keep up with the falling prices for their panels, eliminating profits and making it difficult to invest in the new equipment needed to keep reducing costs and improving solar performance.

For example, Suntech has been promising for years to scale up production of its Pluto solar cells, which generate significantly more electricity than conventional ones (see "The Chinese Solar Machine," January/February 2012, and "Solar's Great Leap Forward," July/August 2010). But that technology has been put on hold. Similarly, General Electric has developed an alternative to conventional silicon solar panels, but last year the company announced that it had to postpone construction of its factory until the market improves.

Although the national Chinese government supported the rapid growth in solar manufacturing capacity, it now says the current situation is unsustainable and recommends allowing the least competitive companies to go under. Such decisions will be crucial, because the recovery of the solar market will depend in part on how fast companies are allowed to fail.

TO MARKET

Hardcourt Data

94Fifty Basketball

COMPANY: InfoMotion Sports Technologies

PRICE: $295

AVAILABILITY: Autumn

Sensors and a microprocessor inside a basketball record thousands of data points about how a player is shooting, dribbling, and moving with the ball and then relays the data to an app on Apple or Android devices. The app points out correctable problems, such as shots that don't arc very high on their way to the basket. That could indicate that the shooters are relying too much on their shoulder muscles and not enough on their wrists. The ball is regulation size and weight, even with the embedded electronics and their battery—which can be recharged by putting the ball on a wireless pad.

QILAI SHEN/IN PICTURES/ CORBIS/AP IMAGES; COURTESY OF 94FIFTY; DATA FROM ENERGY INFORMATION ADMINISTRATION

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Q+A

Miyoung Chun

The Brain Research through Advancing Innovative Neurotechnologies (BRAIN) project, which President Obama announced in his State of the Union address in February, will be a decade-long effort to understand the nature of thought. The project, which inevitably evokes the Human Genome Project, will demand billions in research funding and require the coöperation of many government agencies, universities, and foundations. Miyoung Chun, a molecular geneticist and vice president for science programs at the Kavli Foundation, has been coördinating communication among those involved since planning began 18 months ago. She spoke to Jason Pontin, *MIT Technology Review*'s editor in chief, in March.

What do you hope to map, exactly?
We've made great strides since neurons were recognized [by Santiago Ramón y Cajal more than 100 years ago] as the basic functional unit of the nervous system. We know how to measure the activity of small numbers of neurons—up to a few hundred. Using functional MRI [magnetic resonance imaging], we also know how to measure the activities of patches of large numbers of neurons—from 30,000 to one million. But many critical brain functions involve anywhere from a few thousand to many millions of neurons. BRAIN will generate revolutionary new tools to measure the brain activities in thousands to millions of neurons in order to produce a general theory of the brain.

Why do it?
We want to understand how we reason, how we memorize, how we learn, how we move, how our emotions work. These abilities define us. And yet we hardly understand any of it.

How will nanoscience and nanotechnology contribute to the brain activity map?
The brain functions at the nanoscale. So the tools to study brains must ultimately operate at this level as well. What's really going to be needed is the ability to measure a lot more. Ten to 15 years ago, the time wasn't right; now, it's feasible.

What would be the benefits?
What's the point of measuring more if you don't understand what it means? The purpose of BRAIN is not just to develop tools so that we can read more neurons; we want to *decipher* brain activity. An interdisciplinary network of scientists and engineers will work to make new, powerful prosthetics, treatments for devastating brain disorders, improved educational strategies, and smart technologies that mimic the brain's extraordinary abilities.

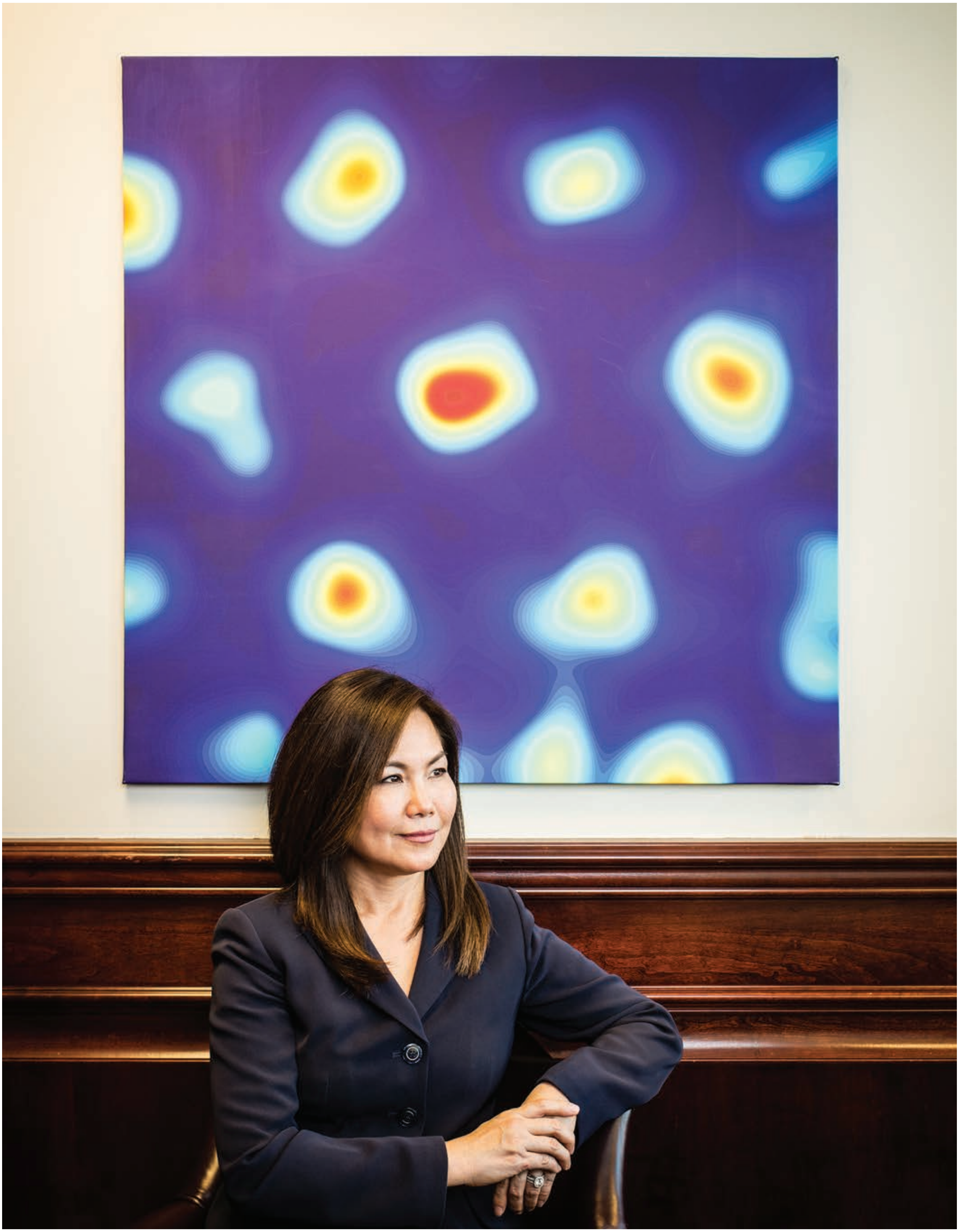
Is the Human Genome Project a good or dumb metaphor for the brain activity map?
There are similarities: the scope of the study, its long-term vision, and the amount of funding it will require. What's dissimilar is the end point. In the case of the Human Genome Project, the end was very clear. As soon as you sequence three billion nucleotides, you're done, right? But for the brain activity map, it's probably imprudent to set a goal to measure the 100 billion neurons in the human brain. For one, we may never achieve such a goal; but more importantly, we don't know if a smaller number will provide us the insights we need.

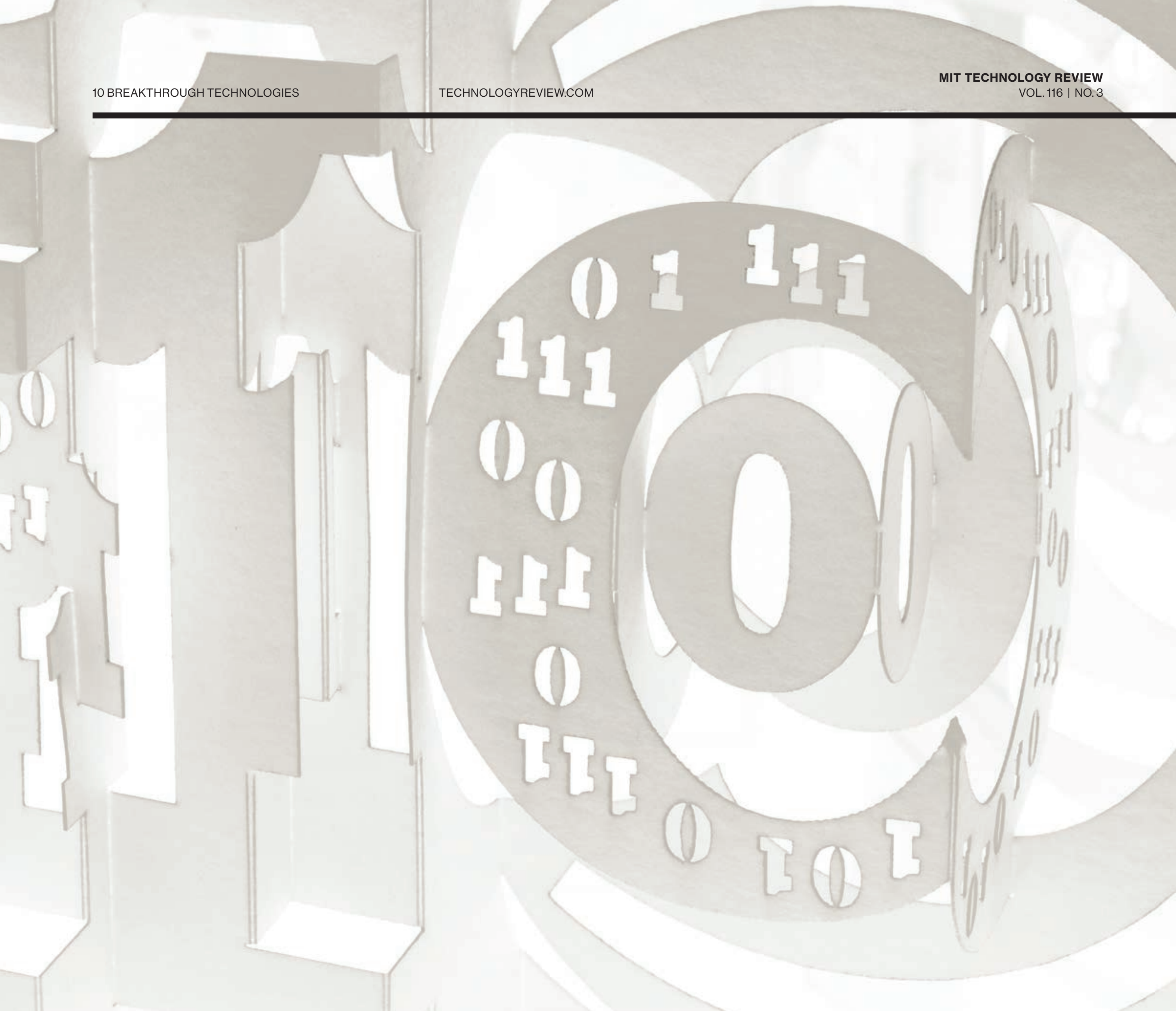
You also mean we can't even anticipate some of the questions that will emerge from the mapping.
Precisely. We don't know what we will learn by measuring and deciphering a million neurons. What we do know is what we have already been able to achieve. For example, John Donoghue [of Brown University] has a patient who had a stroke 15 years ago. By stimulating less than 100 neurons, she could move the arms of a robot and drink her morning coffee. A hundred neurons. Imagine: maybe this patient can walk on her own if John can stimulate 100,000 neurons!

I'd like to ask a private question, if I might. What's the one question that the BRAIN project might answer that you long to understand?
I try not to personalize the project, to be honest.

Well, that's why it's an interesting question.
What's most interesting to me is how our thoughts are molded. Thought seems such a human thing. We assume that other species have thoughts, but *our* thoughts appear to be more … comprehensive. It's thoughts that led us—you and me—to talk about these issues today. Our thoughts are directly related to how we memorize, and how we learn, and how we are able to do so much. But what's the basis for this? It's the reasoning side of the brain that seems to me the most mysterious. But I would think that everyone has their own opinions on why mapping the brain is important. ■

DAVID LAURIDSEN





10 Breakthrough Technologies

SCULPTURE BY INGRID SILIAKUS; PHOTOGRAPH BY GEOFF STEIN

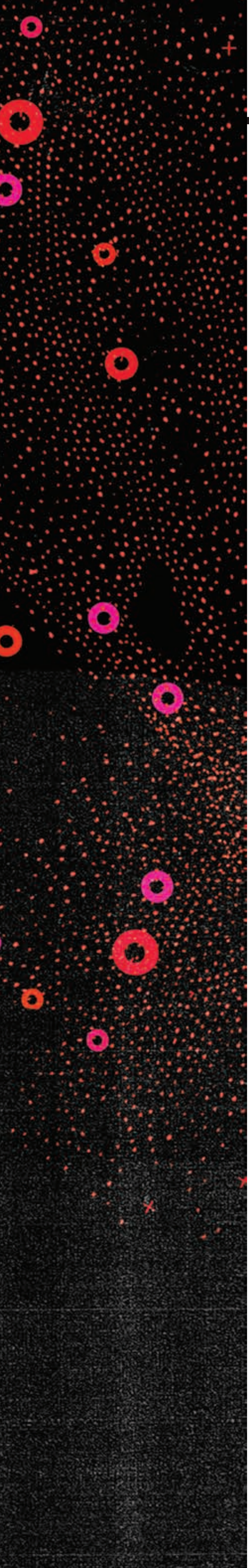
Our definition of a breakthrough is simple: an advance that gives people powerful new ways to use technology. It could be an intuitive design that provides a useful interface (see "Smart Watches") or experimental devices that could allow people who have suffered brain damage to once again form memories ("Memory Implants"). Some could be key to sustainable economic growth ("Additive Manufacturing" and "Supergrids"), while others could change how we communicate ("Temporary Social Media") or think about the unborn ("Prenatal DNA Sequencing"). Some are brilliant feats of engineering ("Baxter"). Others stem from attempts to rethink longstanding problems in their fields ("Deep Learning" and "Ultra-Efficient Solar Power"). As a whole, we intend this annual list not only to tell you which technologies you need to know about, but also to celebrate the creativity that produced them.

—The Editors

Deep Learning

With massive amounts of computational power, machines can now recognize objects and translate speech in real time. Artificial intelligence is finally getting smart.

By Robert D. Hof
Illustration by Jimmy Turrell



When Ray Kurzweil met with Google CEO Larry Page last July, he wasn't looking for a job. A respected inventor who's become a machine-intelligence futurist, Kurzweil wanted to discuss his upcoming book *How to Create a Mind*. He told Page, who had read an early draft, that he wanted to start a company to develop his ideas about how to build a truly intelligent computer: one that could understand language and then make inferences and decisions on its own.

It quickly became obvious that such an effort would require nothing less than Google-scale data and computing power. "I could try to give you some access to it," Page told Kurzweil. "But it's going to be very difficult to do that for an independent company." So Page suggested that Kurzweil, who had never held a job anywhere but his own companies, join Google instead. It didn't take Kurzweil long to make up his mind: in January he started working for Google as a director of engineering. "This is the culmination of literally 50 years of my focus on artificial intelligence," he says.

Kurzweil was attracted not just by Google's computing resources but also by the startling progress the company has made in a branch of AI called deep learning. Deep-learning software attempts to mimic the activity in layers of neurons in the neocortex, the wrinkly 80 percent of the brain where thinking occurs. The software learns, in a very real sense, to recognize patterns in digital representations of sounds, images, and other data.

The basic idea—that software can simulate the neocortex's large array of neurons in an artificial "neural network"—is decades old, and it has led to as many disappointments as breakthroughs. But because of improvements in mathematical formulas and increasingly powerful computers, computer scientists can now model many more layers of virtual neurons than ever before.

With this greater depth, they are producing remarkable advances in speech and image recognition. Last June, a Google deep-learning system that had been shown 10 million images from YouTube videos proved almost twice as good as any previous image recognition effort at identifying objects such as cats. Google also used the technology to cut the error rate on speech recognition in its latest Android mobile software. In October, Microsoft chief research officer Rick Rashid wowed attendees at a lecture in China with a demonstration of speech software that transcribed his spoken words into English text with an error rate of 7 percent, translated them into Chinese-language text, and then simulated his own voice uttering them in Mandarin. That same month, a team of three graduate students and two professors won a contest held by Merck to identify molecules that could lead to new drugs. The group used deep learning to zero in on the molecules most likely to bind to their targets.

Google in particular has become a magnet for deep learning and related AI talent. In March the company bought a startup cofounded by Geoffrey Hinton, a University of Toronto computer science professor who was part of the team that won the Merck contest. Hinton, who will split his time between the university and Google, says he plans to "take ideas out of this field and apply them to real problems" such as image recognition, search, and natural-language understanding, he says.

All this has normally cautious AI researchers hopeful that intelligent machines may finally escape the pages of science fiction. Indeed, machine intelligence is starting to transform everything from communications and computing to medicine, manufacturing, and transportation. The possibilities are apparent in IBM's *Jeopardy!*-winning Watson computer, which uses some deep-learning techniques and is now being trained to help doctors make better decisions. Microsoft has deployed deep learning in its Windows Phone and Bing voice search.

Extending deep learning into applications beyond speech and image recognition will require more conceptual and software breakthroughs, not to mention many more advances in processing power. And we probably won't see machines we all agree

Breakthrough

A method of artificial intelligence that could be generalizable to many kinds of applications.

Why It Matters

Computers would assist humans far more effectively if they could reliably recognize patterns and make inferences about the world.

Key Players

- Google
- Microsoft
- IBM
- Geoffrey Hinton, University of Toronto

can think for themselves for years, perhaps decades—if ever. But for now, says Peter Lee, head of Microsoft Research USA, "deep learning has reignited some of the grand challenges in artificial intelligence."

BUILDING A BRAIN

There have been many competing approaches to those challenges. One has been to feed computers with information and rules about the world, which required programmers to laboriously write software that is familiar with the attributes of, say, an edge or a sound. That took lots of time and still left the systems unable to deal with ambiguous data; they were limited to narrow, controlled applications such as phone menu systems that ask you to make queries by saying specific words.

Neural networks, developed in the 1950s not long after the dawn of AI research, looked promising because they attempted to simulate the way the brain worked, though in greatly simplified form. A program maps out a set of virtual neurons and then assigns random numerical values, or "weights," to connections between them. These weights determine how each simulated neuron responds—with a mathematical output between 0 and 1—to a digitized feature such as an edge or a shade of blue in an image, or a particular energy level at one frequency in a phoneme, the individual unit of sound in spoken syllables.

Programmers would train a neural network to detect an object or phoneme by blitzing the network with digitized versions of images containing those objects or sound waves containing those phonemes. If the network didn't accurately recognize a particular pattern, an algorithm would adjust the weights. The eventual goal of this training was to get the network to consistently recognize the patterns in speech or sets of images that we humans know as, say, the phoneme "d" or the image of a dog. This is much the same way a child learns what a dog is by noticing the details of head shape, behavior, and the like in furry, barking animals that other people call dogs.

Some of today's artificial neural networks can train themselves to recognize complex patterns.

But early neural networks could simulate only a very limited number of neurons at once, so they could not recognize patterns of great complexity. They languished through the 1970s.

In the mid-1980s, Hinton and others helped spark a revival of interest in neural networks with so-called "deep" models that made better use of many layers of software neurons. But the technique still required heavy human involvement: programmers had to label data before feeding it to the network. And complex speech or image recognition required more computer power than was then available.

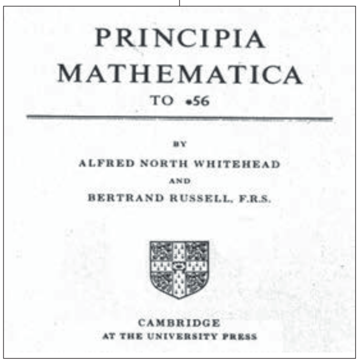
Finally, however, in the last decade Hinton and other researchers made some fundamental conceptual breakthroughs. In 2006, Hinton developed a more efficient way to teach individual layers of neurons. The first layer learns primitive features, like an edge in an image or the tiniest unit of speech sound. It does this by finding combinations of digitized pixels or sound waves that occur more often than they should by chance. Once that layer accurately recognizes those features, they're fed to the next layer, which trains itself to recognize more complex features, like a corner or a combination of speech sounds. The process

AI's Evolution

1948 1950 1955 1956 1968 1973

The Manchester Small-Scale Experimental Machine is the first computer to execute a program stored in electronic memory.

Alan Turing's paper "Computing Machinery and Intelligence" introduces the concept of the Turing test.



Work begins on the "Logic Theorist," which many consider the first AI program. It proves 38 of the first 52 theorems in *Principia Mathematica,* an early-20th-century attempt to devise a set of rules for all mathematical truths.

John McCarthy organizes a conference at Dartmouth College with prominent minds in the field and coins the term "artificial intelligence."

is repeated in successive layers until the system can reliably recognize phonemes or objects.

Like cats. Last June, Google demonstrated one of the largest neural networks yet, with more than a billion connections. A team led by Stanford computer science professor Andrew Ng and Google Fellow Jeff Dean showed the system images from 10 million randomly selected YouTube videos. One simulated neuron in the software model fixated on images of cats. Others focused on human faces, yellow flowers, and other objects. And thanks to the power of deep learning, the system identified these discrete objects even though no humans had ever defined or labeled them.

What stunned some AI experts, though, was the magnitude of improvement in image recognition. The system correctly categorized objects and themes in the YouTube images 16 percent of the time. That might not sound impressive, but it was 70 percent better than previous methods. And, Dean notes, there were 22,000 categories to choose from; correctly slotting objects into some of them required, for example, distinguishing between two similar varieties of skate fish. That would have been challenging even for most humans. When the system was asked to sort the images into 1,000 more general categories, the accuracy rate jumped above 50 percent.

BIG DATA

Training the many layers of virtual neurons in the experiment took 16,000 computer processors—the kind of computing infrastructure that Google has developed for its search engine and other services. At least 80 percent of the recent advances in AI can be attributed to the availability of more computer power, reckons Dileep George, cofounder of the machine-learning startup Vicarious.

There's more to it than the sheer size of Google's data centers, though. Deep learning has also benefited from the company's method of splitting computing tasks among many machines so they can be done much more quickly. That's a technology Dean helped develop earlier in his 14-year career at Google. It vastly speeds up the training of deep-learning neural networks as well, enabling Google to run larger networks and feed a lot more data to them.

Already, deep learning has improved voice search on smartphones. Until last year, Google's Android software used a method that misunderstood many words. But in preparation for a new release of Android last July, Dean and his team helped replace part of the speech system with one based on deep learning. Because the multiple layers of neurons allow for more precise training on the many variants of a sound, the system can recognize scraps of sound more reliably, especially in noisy environments such as subway platforms. Since it's likelier to understand what was actually uttered, the result it returns is likelier to be accurate as well. Almost overnight, the number of errors fell by up to 25 percent—results so good that many reviewers now deem Android's voice search smarter than Apple's more famous Siri voice assistant.

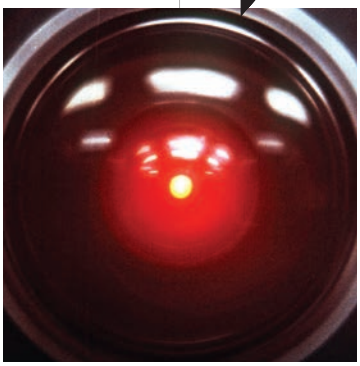
For all the advances, not everyone thinks deep learning can move artificial intelligence toward something rivaling human intelligence. Some critics say deep learning and AI in general ignore too much of the brain's biology in favor of brute-force computing.

One such critic is Jeff Hawkins, founder of Palm Computing, whose latest venture, Numenta, is developing a

1997

2011

Just what do you think you're doing, Dave?



The movie *2001: A Space Odyssey* introduces a popular notion of AI through the computer HAL.

Sir James Lighthill reports to British officials on a "pronounced feeling of disappointment" in AI's accomplishments. The report supports declines in government funding during the "AI winter" of the 1970s and '80s.

IBM's Deep Blue supercomputer defeats world chess champion Garry Kasparov in a six-game match. Kasparov had beaten IBM computers in two previous matches.

IBM's Watson wins *Jeopardy!*, defeating two of the game show's most successful contestants of all time.

machine-learning system that is biologically inspired but does not use deep learning. Numenta's system can help predict energy consumption patterns and the likelihood that a machine such as a windmill is about to fail. Hawkins, author of *On Intelligence*, a 2004 book on how the brain works and how it might provide a guide to building intelligent machines, says deep learning fails to account for the concept of time. Brains process streams of sensory data, he says, and human learning depends on our ability to recall sequences of patterns: when you watch a video of a cat doing something funny, it's the motion that matters, not a series of still images like those Google used in its experiment. "Google's attitude is: lots of data makes up for everything," Hawkins says.

But if it doesn't make up for everything, the computing resources a company like Google throws at these problems can't be dismissed. They're crucial, say deep-learning advocates, because the brain itself is still so much more complex than any of today's neural networks. "You need lots of computational resources to make the ideas work at all," says Hinton.

WHAT'S NEXT

Although Google is less than forthcoming about future applications, the prospects are intriguing. Clearly, better image search would help YouTube, for instance. And Dean says deep-learning models can use phoneme data from English to more quickly train systems to recognize the spoken sounds in other languages. It's also likely that more sophisticated image recognition could make Google's self-driving cars much better. Then there's search and the ads that underwrite it. Both could see vast improvements from any technology that's better and faster at recognizing what people are really looking for—maybe even before they realize it.

This is what intrigues Kurzweil, 65, who has long had a vision of intelligent machines. In high school, he wrote software that enabled a computer to create original music in various classical styles, which he demonstrated in a 1965 appearance on the TV show *I've Got a Secret*. Since then, his inventions have included several firsts—a print-to-speech reading machine, software that could scan and digitize printed text in any font, music synthesizers that could re-create the sound of orchestral instruments, and a speech recognition system with a large vocabulary.

Today, he envisions a "cybernetic friend" that listens in on your phone conversations, reads your e-mail, and tracks your every move—if you let it, of course—so it can tell you things you want to know even before you ask. This isn't his immediate goal at Google, but it matches that of Google cofounder Sergey Brin, who said in the company's early days that he wanted to build the equivalent of the sentient computer HAL in *2001: A Space Odyssey*—except one that wouldn't kill people.

Sergey Brin has said he wants to build a benign version of HAL in *2001: A Space Odyssey*.

For now, Kurzweil aims to help computers understand and even speak in natural language. "My mandate is to give computers enough understanding of natural language to do useful things—do a better job of search, do a better job of answering questions," he says. Essentially, he hopes to create a more flexible version of IBM's Watson, which he admires for its ability to understand *Jeopardy!* queries as quirky as "a long, tiresome speech delivered by a frothy pie topping." (Watson's correct answer: "What is a meringue harangue?")

Kurzweil isn't focused solely on deep learning, though he says his approach to speech recognition is based on similar theories about how the brain works. He wants to model the actual meaning of words, phrases, and sentences, including ambiguities that usually trip up computers. "I have an idea in mind of a graphical way to represent the semantic meaning of language," he says.

That in turn will require a more comprehensive way to graph the syntax of sentences. Google is already using this kind of analysis to improve grammar in translations. Natural-language understanding will also require computers to grasp what we humans think of as common-sense meaning. For that, Kurzweil will tap into the Knowledge Graph, Google's catalogue of some 700 million topics, locations, people, and more, plus billions of relationships among them. It was introduced last year as a way to provide searchers with answers to their queries, not just links.

Finally, Kurzweil plans to apply deep-learning algorithms to help computers deal with the "soft boundaries and ambiguities in language." If all that sounds daunting, it is. "Natural-language understanding is not a goal that is finished at some point, any more than search," he says. "That's not a project I think I'll ever finish."

Though Kurzweil's vision is still years from reality, deep learning is likely to spur other applications beyond speech and image recognition in the nearer term. For one, there's drug discovery. The surprise victory by Hinton's group in the Merck contest clearly showed the utility of deep learning in a field where few had expected it to make an impact.

That's not all. Microsoft's Peter Lee says there's promising early research on potential uses of deep learning in machine vision—technologies that use imaging for applications such as industrial inspection and robot guidance. He also envisions personal sensors that deep neural networks could use to predict medical problems. And sensors throughout a city might feed deep-learning systems that could, for instance, predict where traffic jams might occur.

In a field that attempts something as profound as modeling the human brain, it's inevitable that one technique won't solve all the challenges. But for now, this one is leading the way in artificial intelligence. "Deep learning," says Dean, "is a really powerful metaphor for learning about the world."

Contributing editor Robert D. Hof wrote about Apple TV in the March/April issue.

PREVIOUS SPREAD, FROM LEFT: KGGUCWA/CREATIVE COMMONS; NATIONAL PORTRAIT GALLERY, LONDON; UNCREDITED; AP PHOTOS; MGM/PHOTOFEST; UCL; STAN HONDA/AFP/GETTY IMAGES; BEN HIDER/GETTY IMAGES

MITSloan
CIO SYMPOSIUM

WEDNESDAY, MAY 22, 2013
Full day event
MIT Kresge Auditorium
Cambridge, MA

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May 22, 2013

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Baxter: The Blue-Collar Robot

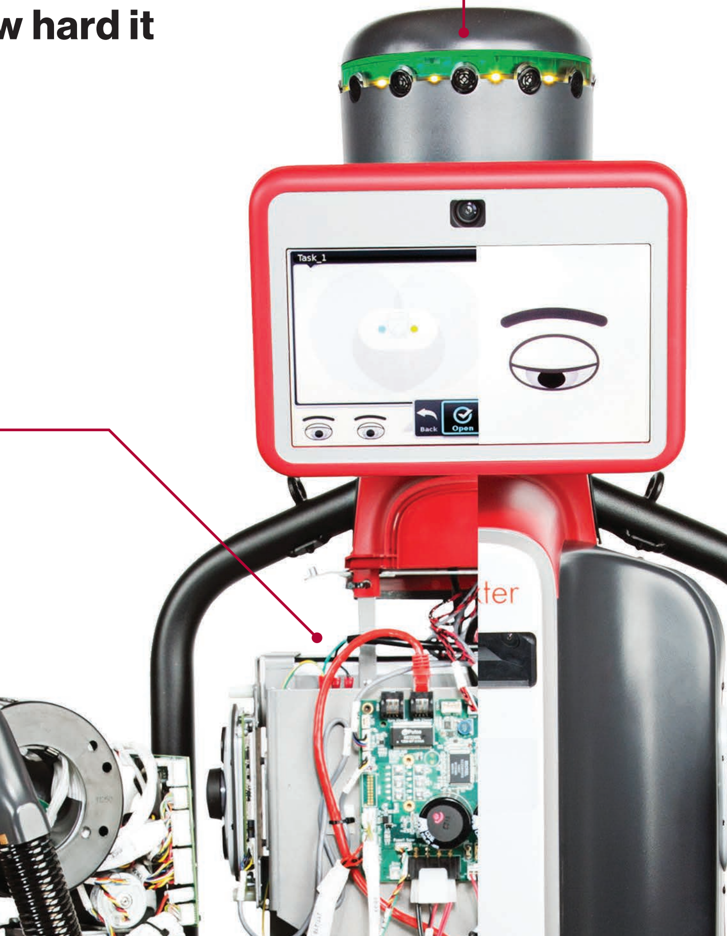
Rethink Robotics' new creation is easy to interact with, but the innovations behind the robot show just how hard it is to get along with people.

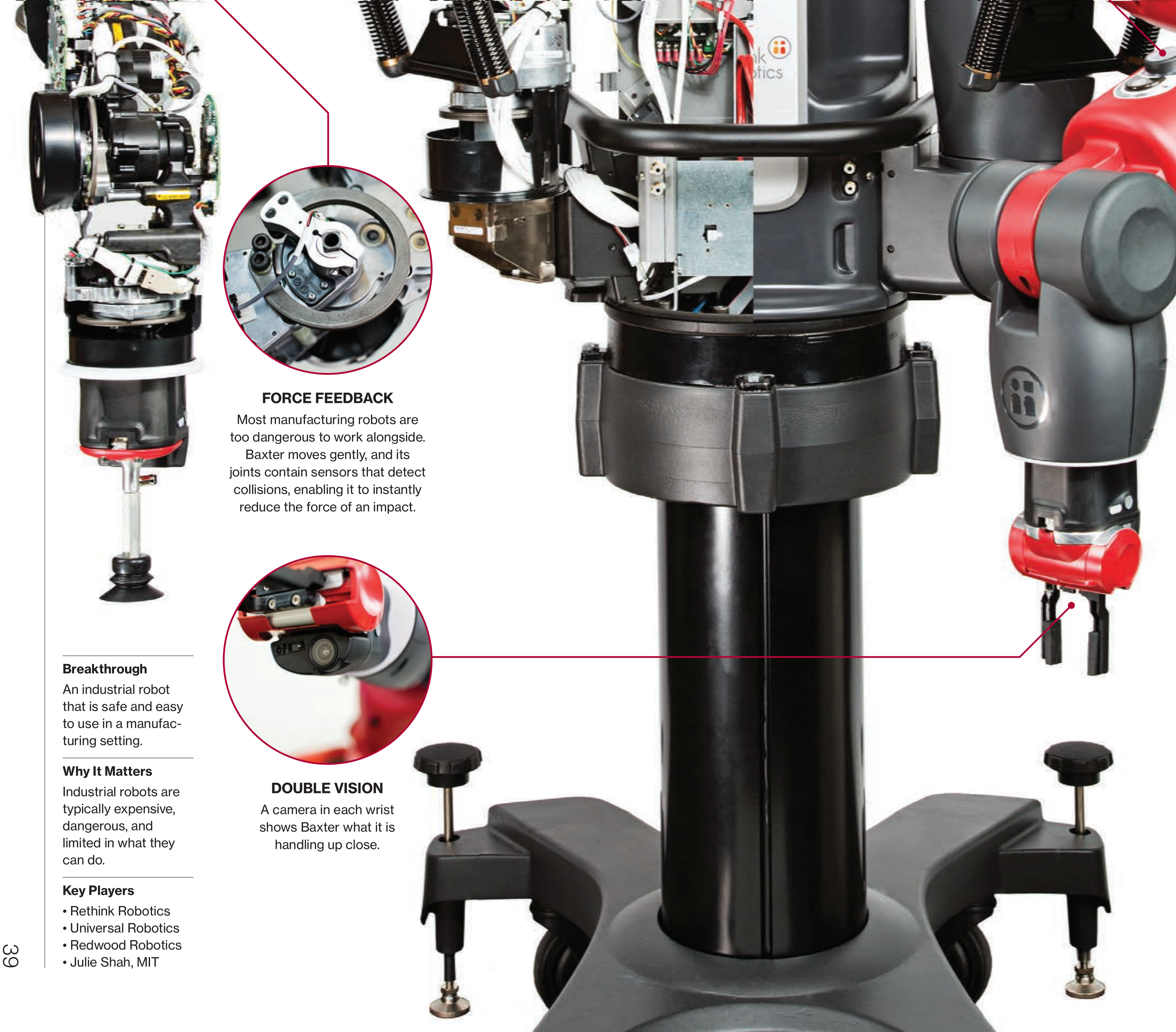
By Will Knight | Photographs by Ken Richardson

THE EXPRESSION SAYS IT ALL
Baxter's face indicates its status and where its attention is focused. It can also sense the location of people nearby, thanks to a ring of sonar sensors around its crown.

HANDS-ON TRAINING
Workers teach Baxter to perform a task by moving its arms, but they can access more features using dials and buttons on its forearms.

CENTRAL COMMAND
Baxter costs far less than most industrial robots, in part because its software runs on an ordinary personal computer, which is embedded in its chest.





FORCE FEEDBACK

Most manufacturing robots are too dangerous to work alongside. Baxter moves gently, and its joints contain sensors that detect collisions, enabling it to instantly reduce the force of an impact.

DOUBLE VISION

A camera in each wrist shows Baxter what it is handling up close.

Breakthrough

An industrial robot that is safe and easy to use in a manufacturing setting.

Why It Matters

Industrial robots are typically expensive, dangerous, and limited in what they can do.

Key Players

- Rethink Robotics
- Universal Robotics
- Redwood Robotics
- Julie Shah, MIT

Reading the DNA of fetuses is the next frontier of the genome revolution. Do you really want to know the genetic destiny of your unborn child?

Breakthrough

Sequencing the DNA of a fetus from a pregnant woman's blood.

Why It Matters

Tomorrow's children could be born with a complete list of their genetic strengths and weaknesses.

Key Players

- Illumina
- Verinata
- Stanford University
- Jay Shendure, University of Washington

Prenatal DNA Sequencing

By Antonio Regalado

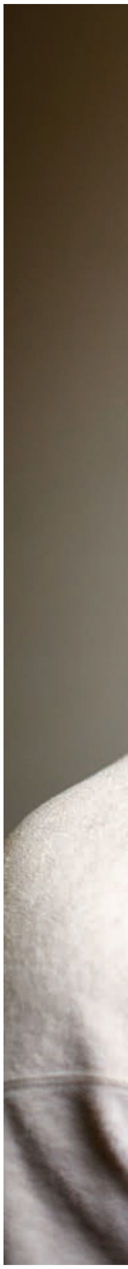
Earlier this year Illumina, the maker of the world's most widely used DNA sequencing machines, agreed to pay nearly half a billion dollars for Verinata, a startup in Redwood City, California, that has hardly any revenues. What Verinata does have is technology that can do something as ethically fraught as it is inevitable: sequence the DNA of a human fetus before birth.

Verinata is one of four U.S. companies already involved in a rapidly expanding market for prenatal DNA testing using Illumina's sequencers. Their existing tests, all launched in the last 18 months, can detect Down syndrome from traces of fetal DNA found in a syringeful of the mother's blood. Until now, detecting Down syndrome has meant grabbing fetal cells from the placenta or the amniotic fluid, procedures that carry a small risk of miscarriage.

The noninvasive screen is so much safer and easier that it's become one of the most quickly adopted tests ever and an important new medical application for Illumina's DNA sequencing instruments, which have so far been used mainly in research labs. In January, Illumina's CEO, Jay Flatley, told investors that he expects the tests will eventually be offered to as many as two million women a year in the United States, representing half of all pregnancies—up from around 250,000 mothers, mostly older, who now undergo the invasive tests. "It's unprecedented in medical testing how fast this has gone

Portrait by Frank Rogozienski/Wonderful Machine

The Executive: *Illumina CEO Jay Flatley is looking to pregnancy as a new market for DNA sequencing.*



The Biophysicist: *Stephen Quake showed how the genome of an unborn child could be revealed.*

Sequencing the DNA in the blood of a pregnant woman could reveal the full genetic code of a fetus.

from lab research to acceptance," says Diana Bianchi, executive director of the Mother Infant Research Institute at Tufts University and the chief clinical advisor to Verinata. "It's a huge impact for any technology in its first year."

But this is likely to be just the start for prenatal DNA sequencing. The same labs and companies that launched the Down syndrome tests, like Verinata, have also figured out how they can get much more information from a mother's bloodstream, including the complete genome sequence of her fetus. That's a technical breakthrough, and maybe a commercial one, too. Pregnancy, with its hopes, anxieties, and frequent doctor's visits, could be where genome sequencing finally finds a major consumer application.

"I think that we are going to sequence the genome of everyone—of every fetus—in the first trimester, at least in part," says Arthur Beaudet, a pediatrician and head of human genetics at the Baylor College of Medicine, in Houston. Today some patients have their genomes sequenced to shed light on genetic diseases or illnesses like cancer, but one day people won't wait until they're sick. "We are already going to know the data at birth," he says.

That won't happen right away. For one thing, sorting out a fetus's exact DNA code via its mother's blood requires a huge amount of repeated sequencing, making it too expensive for routine use. (Illumina currently charges $9,500 to sequence the genome of an adult, and so far attempts to sequence fetal DNA have cost much more.) And there are still technical problems: the fetal genome results are still not accurate enough for making diagnoses. Ethically, too, the technology is a minefield. If we learn the genetic destiny of our children while they are still in the womb, what kinds of choices might we make?

"Technically, all this is possible before we've figured out whether we should be doing it," says Jay Shendure, a genome scientist at the University of Washington. "You've got the whole genome—then what do you do with that? There are a lot of things that will have to get ironed out." Shendure works with Ariosa, one of Verinata's competitors. Last summer, his was one of two U.S. labs to demonstrate how the fetal genome might be revealed from a pregnant woman's blood. He says the studies conducted so far on fetuses, including his own study, have been retrospective—they studied blood samples stored by hospitals. But Shendure says he is now working with doctors at Stanford to implement the technology during an actual pregnancy. In other words, as early as this year the first human whose complete genetic code is known in advance could be born.

Full Genome

In 1997, a Hong Kong scientist named Dennis Lo showed that a pregnant woman's blood contains trillions of bits of DNA from her baby. The DNA comes from cells in the placenta that have died and ruptured. By Lo's estimate, as much as 15 percent of the free-floating DNA in a mother's bloodstream is the fetus's. High-speed DNA sequencing can turn those fragments into a wealth of information.

To detect Down syndrome, which causes cognitive and physical impairments, geneticists have typically looked through a microscope to count the number of chromosomes in fetal cells captured in a procedure called amniocentesis. An extra copy of chromosome 21 means the fetus is affected, and about 65 percent of U.S. women confronted with that diagnosis choose an abortion.

To get the same information from a few milliliters of blood, scientists use a trick first suggested by Lo. They randomly sequence millions of those circulating DNA fragments, often only 50 to 500 DNA letters long. Then, using a computer program, they line up the sequences against a map of human chromosomes. After that, it's a counting exercise: if more bits than expected match up with chromosome 21, that's evidence of an extra copy somewhere, and the fetus probably has Down syndrome. The method is clever because it doesn't matter that the

Portrait by Max Whittaker

mother's DNA and that of the fetus are mixed together and are, in fact, partly identical. The same approach can find extra copies, or trisomies, of chromosomes 18 and 13, as well as missing or duplicate X chromosomes—all causes of birth defects in infants.

Last July, the scientific founder of Verinata, Stanford University biophysicist Stephen Quake, showed how in addition to detecting extra chromosomes, sequencing the DNA in the blood of a pregnant woman could reveal the full genetic code of a fetus, letter for letter. Shendure's lab did something similar, as have two teams in China.

Reconstructing the six billion chemical letters of a fetal genome from those DNA fragments isn't easy. It requires lots of extra sequencing to see past the mother's genes. Shendure says the bill came to $50,000, and Quake's lab cut its experiment short after running up similar expenses. Yet the work showed that a genome readout might act as a kind of universal test not only for extra chromosomes but for common congenital diseases, too. Those are conditions, like cystic fibrosis or beta-thalassemia, that are caused when a person inherits two defective versions of a particular gene, one from each parent. There are about 3,000 such diseases whose precise genetic cause is known.

Some 200 other maladies, including some cases of autism, are caused by known duplications or deletions of larger swaths of DNA. A genome test would show all of them.

Quake says proving that a full genome readout is possible was the "logical extension" of the underlying technology. Yet what's much less clear to Quake and others is whether a universal DNA test will ever become important or routine in medicine, as the more targeted test for Down syndrome has become. "We did it as an academic exercise, just for the hell of it," he says. "But if you ask me, 'Are we going to know the genomes of children at birth?' I'd ask you, 'Why?' I get stuck on the why." Quake says he's now refining the technology so that it could be used to inexpensively pull out information on just the most medically important genes.

The problem is that it's simply not clear whether doctors, or parents, really want so much information. That's a challenge Illumina has already encountered in its Individual Genome Sequencing service, with which it first offered genome

sequencing to medical patients in 2009. Yet the service hasn't exactly taken off. Illumina now decodes about one genome a day for medical reasons (mostly of adults with cancer or young children with mystery ailments). What's clear is that the ability to gather DNA data has outstripped the ability to understand that information, which means it has also outstripped the medical demand for it. "Showing the utility of the genome is the main challenge going forward," says Mostafa Ronaghi, Illumina's chief technical officer.

Why Worry?

Illumina's Jay Flatley is the person who engineered the Verinata takeover. The 59-year-old chief executive has led his company to $1.15 billion in revenue by besting other makers of sequencing machines and last year also resisted a hostile takeover offer of $6.7 billion from Roche, the world's largest diagnostics firm. Flatley convinced shareholders not to accept the deal, promising to make genomics a "routine" part of people's lives, increasing Illumina's profits.

Flatley has predicted for years that genome sequencing will become a reality in medicine—specifically, that every child will get its genome sequenced "at birth." So does he now think it could happen even earlier, during pregnancy? In a field with a reputation for wild, unfulfilled promises, Flatley is known as a cool realist whose predictions often come true. "It's not the technology that is limiting. It will be clearly possible to do this in two years," he says. But a commercial market is much further away than that. "Most people would have an inherently negative reaction, and for good reason."

The problem is that having more information about a fetus's traits could present doctors and parents with a deluge of information they aren't able to understand or act on. And if they do act, that could be controversial, too. "Whole-genome sequencing could open Pandora's box," says Henry Greely, a law professor who studies bioethics at Stanford. "You'd have the whole sequence, so you might be able to look for straight nose, curly hair. How many parents are going to abort a fetus because of male pattern baldness? I don't think many. But it's probably more than zero." Greely says that because fetal DNA is detectable in the bloodstream so early in pregnancy—as early as six or eight weeks—the pregnancy could be ended relatively easily.

One doesn't have to look far for a case that could stir concerns about eugenics. This year, with its chromosome-counting test, Verinata began offering a screen for Klinefelter syndrome, in which males have an extra X chromosome. The condition—which causes reduced testosterone, feminine features, and often infertility—affects 1 in 1,000 men, so about as many American men have it as live in Pittsburgh. What's more, the symptoms can be so mild that some of those affected don't even realize it. Even so, about half of women choose to end a Klinefelter pregnancy. If Verinata's test is widely applied, many more women will have to decide whether to make that choice.

Dennis Lo believes that as fetal DNA sequencing advances, test makers should restrict themselves to reporting just the 20 or so most common serious diseases. "We are going to face the challenge of what do you look for and how do you counsel women," he says. "I think we must use the technology in an ethical fashion and should refrain from analyzing things that are not life-threatening. Like predisposition to diabetes when someone is 40 years old. We don't even know what medicine would be in 40 years, so why worry the mother about that?"

The Ethicist: *Morris Foster wonders if we will treat children differently if we know their DNA.*

While adults can decide whether to undergo genome sequencing, an unborn child can't consent to knowing its genes.

Morris Foster, an anthropologist at the University of Oklahoma who heads a panel of ethics advisors that Illumina has hired, says he and Flatley have discussed whole-genome sequencing of the unborn. "It's clearly something that is on the horizon," he says. "My advice to Illumina is, 'You are a lab receiving a physician order. You don't second-guess the physician.' The ethical advice I would

Portrait by Shane Brown

give to a physician is much more complex and nuanced."

Medical groups are still struggling to formulate rules for handling genomic data for adults. And Foster says prenatal tests would make the legal and ethical obligations facing a doctor that much more complicated. For one thing, he says, while adults can decide whether to undergo genome sequencing, an unborn child can't consent to knowing its genes. And that knowledge could affect a person's entire life. "The whole sequence invariably tells you more information than you can act on," he says. "Yet because you can generate that data, it's likely that we will. Instead of stopping people from knowing things about themselves, you'd want to use it in a way that doesn't create anxiety or strain families and medical resources."

Foster fears that, if anything, people will put too much stock in genes. "I think the greatest risk is the overinterpretation of genetic findings. That doctors will think a variant associated with diabetes means you are going to get diabetes. Or that the absence of it means you are not," he says. For parents, such probabilities might seem like certainties, even if they aren't really. "If they bring a child to term with a genetic-based risk, would it cause the parents to treat the child otherwise?"

Right now, Illumina's medical genome lab takes orders only for adult DNA data, or for sick children. And its new subsidiary Verinata carries out only an improved version of fetal chromosome tests that are familiar to doctors. Even so, given the quick advance of prenatal DNA technology in the lab, Flatley thinks society may need some new laws. "What would help a lot is legislation that says you can't do certain things," he says. Partly, that argument is self-serving: a messy social debate is going to slow down genome sequencing. On the wall of the company cafeteria, next to a towering row of framed patents Illumina has won, hangs a newspaper article from 2009, in which Flatley is quoted as predicting that all newborns will have their genomes sequenced by 2019, six years from now. In it, the CEO struck a by now familiar note. The limits to the technology of DNA sequencing, and to his company's prospects, "are sociological," he said. The only constraints are "when and where people think it can be applied."

Antonio Regalado is MIT Technology Review*'s senior business editor.*

Messages that quickly self-destruct could enhance the privacy of online communication and make people feel freer to be spontaneous.

Temporary Social Media

By Jeffrey Rosen and Christine Rosen
Illustration by Brian Cronin

One essential aspect of privacy is the ability to control how much we disclose to others. Unfortunately, we've lost much of that control now that every photo, chat, or status update posted on a social-media site can be stored in the cloud: even though we intended to share that information with someone, we don't necessarily want it to stay available, out of context, forever. The weight of our digital pasts is emerging as the central privacy challenge of our time.

But what if people could make their posts vanish automatically—making social media more of an analogue to everyday conversations that aren't recorded for posterity? That's the promise of services such as Snapchat, a mobile-phone app whose popularity has increased dramatically during the past year. Evan Speigel and Bobby Murphy, who met as undergrads at Stanford, came up with the idea two years ago, around the time New York congressman Anthony Weiner accidentally made racy photos of himself public on Twitter and was forced to resign. Snapchat lets users take photos or short videos and then decide how long they will be visible to the recipient. After 10 seconds or less, the images disappear forever. (Not for nothing is Snapchat's mascot a picture of a grinning ghost.)

From the beginning, the service appealed to teenagers looking for a more private way of sending each other sexy pictures. But "sexting" alone can't account for all 100 million photos and videos exchanged on Snapchat every day. And Mark Zuckerberg must worry that Snapchat addresses some misgivings people have about privacy on Facebook; in December, Facebook launched a Snapchat copycat app called Poke.

What makes temporary social media so appealing? Snapchat's founders often remark that they wanted to give people a way to express themselves through something besides the idealized self-portraits many feel required to maintain on social-media sites. Snapchats might be more exciting to send and receive than other social-media posts because they are ephemeral, but they are also arguably a more natural way to communicate. Whereas Facebook and Twitter record and store your every offhand observation and casual interaction, interactions in temporary social media can be something like brief, in-person conversations: you can speak your mind without worrying that what you say will be part of your digital dossier forever.

Although Snapchat's posture as the anti-Facebook is a large part of its allure, eventually its founders will have to confront some of the same privacy challenges that have vexed Facebook. Snapchat contains an obvious technological vulnerability: images that were meant to vanish can still be saved if the recipient uses a screen-capture feature to take a picture of the message during the seconds it appears. (If the recipient does this, Snapchat notifies the sender, but by then it's too late to stop the image from being preserved and shared.) Moreover, while Snapchat promises to erase photos from its servers, the company's privacy policy adds that it "cannot guarantee that the message data will be deleted in every case." As soon as a racy Snapchat picture of a celebrity goes viral, trust in the company could be eroded.

But regardless of the fate of Snapchat in particular, the idea of temporary social media is important because the ability to be candid and spontaneous—and to be that way with only some people and not others—is the essence of friendship, individuality, and creativity. Facebook and Twitter do make it possible for their members to wall off posts from the wider world and share them only with trusted people in certain circles. But since those posts still last forever, this capacity for limited sharing is technologically insecure. To the degree that temporary social networks increase our sense of control over the conditions of our personal exposure, they represent a first step toward a more nuanced kind of digital connection—one acknowledging that our desire to share can coexist with a desire for reticence, privacy, and the possibility of a fresh start. T

Jeffrey Rosen, a law professor at George Washington University, is legal affairs editor of The New Republic. *Christine Rosen, a Schwartz Fellow at the New America Foundation, is a senior editor at* The New Atlantis: A Journal of Technology & Society.

Breakthrough
A social-media service that replicates the unrecorded nature of ordinary conversation.

Why It Matters
Sites such as Facebook and Twitter are becoming permanent records of our interactions.

Key Players
- Snapchat
- Gryphn
- Burn Note
- Wickr

Ultra-Efficient Solar Power

Doubling the efficiency of solar devices would completely change the economics of renewable energy. Here is a design that just might make it possible.

By Mike Orcutt | Illustration by John MacNeill

Breakthrough

Managing light to harness more of sunlight's energy.

Why It Matters

Higher efficiency would make solar power more competitive with fossil fuels.

Key Players

- Harry Atwater, Caltech
- Albert Polman, AMOLF
- Eli Yablonovitch, University of California, Berkeley
- Dow Chemical

Harry Atwater thinks his lab can make an affordable device that produces more than twice the solar power generated by today's panels. The feat is possible, says the Caltech professor of materials science and applied physics, because of recent advances in the ability to manipulate light at a very small scale.

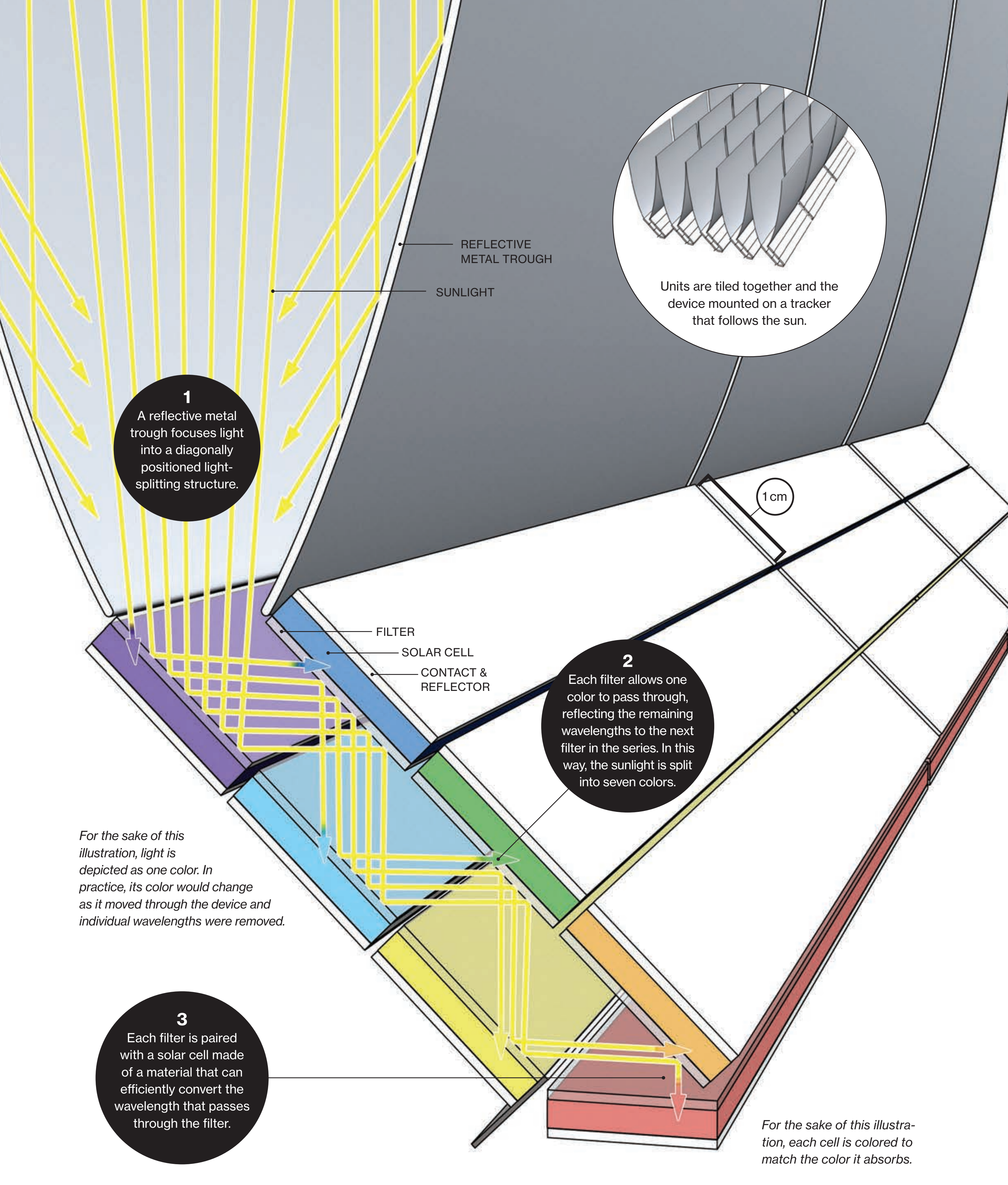
Solar panels on the market today consist of cells made from a single semiconducting material, usually silicon. Since the material absorbs only a narrow band of the solar spectrum, much of sunlight's energy is lost as heat: these panels typically convert less than 20 percent of that energy into electricity. But the device that Atwater and his colleagues have in mind would have an efficiency of at least 50 percent. It would use a design that efficiently splits sunlight, as a prism does, into six to eight component wavelengths—each one of which produces a different color of light. Each color would then be dispersed to a cell made of a semiconductor that can absorb it.

Atwater's team is working on three designs. In one (see illustration), for which the group has made a prototype, sunlight is collected by a reflective metal trough and directed at a specific angle into a structure made of a transparent insulating material. Coating the outside of the transparent structure are multiple solar cells, each made from one of six to eight different semiconductors. Once light enters the material, it encounters a series of thin optical filters. Each one allows a single color to pass through to illuminate a cell that can absorb it; the remaining colors are reflected toward other filters designed to let them through.

Another design would employ nanoscale optical filters that could filter light coming from all angles. And a third would use a hologram instead of filters to split the spectrum. While the designs are different, the basic idea is the same: combine conventionally designed cells with optical techniques to efficiently harness sunlight's broad spectrum and waste much less of its energy.

It's not yet clear which design will offer the best performance, says Atwater. But the devices envisioned would be less complex than many electronics on the market today, he says, which makes him confident that once a compelling prototype is fabricated and optimized, it could be commercialized in a practical way.

Achieving ultrahigh efficiency in solar designs should be a primary goal of the industry, argues Atwater, since it's now "the best lever we have" for reducing the cost of solar power. That's because prices for solar panels have plummeted over the past few years, so continuing to focus on making them less expensive would have little impact on the overall cost of a solar power system; expenses related to things like wiring, land, permitting, and labor now make up the vast majority of that cost. Making modules more efficient would mean that fewer panels would be needed to produce the same amount of power, so the costs of hardware and installation could be greatly reduced. "Within a few years," Atwater says, "there won't be any point to working on technology that has efficiency that's less than 20 percent."


REFLECTIVE
METAL TROUGH
SUNLIGHT
Units are tiled together and the device mounted on a tracker that follows the sun.
1
A reflective metal trough focuses light into a diagonally positioned light-splitting structure.
1 cm
FILTER
SOLAR CELL
CONTACT &
REFLECTOR
2
Each filter allows one color to pass through, reflecting the remaining wavelengths to the next filter in the series. In this way, the sunlight is split into seven colors.
For the sake of this illustration, light is depicted as one color. In practice, its color would change as it moved through the device and individual wavelengths were removed.
3
Each filter is paired with a solar cell made of a material that can efficiently convert the wavelength that passes through the filter.
For the sake of this illustration, each cell is colored to match the color it absorbs.

Big Data from Cheap Phones

Collecting and analyzing information from simple cell phones can provide surprising insights into how people move about and behave—and even help us understand the spread of diseases.

By David Talbot
Illustration by Dan Page

At a computer in her office at the Harvard School of Public Health in Boston, epidemiologist Caroline Buckee points to a dot on a map of Kenya's western highlands, representing one of the nation's thousands of cell-phone towers. In the fight against malaria, Buckee explains, the data transmitted from this tower near the town of Kericho has been epidemiological gold.

When she and her colleagues studied the data, she found that people making calls or sending text messages originating at the Kericho tower were making 16 times more trips away from the area than the regional average. What's more, they were three times more likely to visit a region northeast of Lake Victoria that records from the health ministry identified as a malaria hot spot. The tower's signal radius thus covered a significant waypoint for transmission of malaria, which can jump from human to human via mosquitoes. Satellite images revealed the likely culprit: a busy tea plantation that was probably full of migrant workers. The implication was clear, Buckee says. "There will be a ton of infected [people] there."

This work is now feeding into a new set of predictive models she is building. They show, for example, that even though malaria cases were seen at the tea plantation, taking steps to control malaria there would have less effect on the disease's spread than concentrating those efforts at the source: Lake Victoria. That region has long been understood as a major center of malaria, but what hasn't been available before is detailed information about the patterns of human travel there: how many people are coming and going, when they're arriving and departing, which specific places they're coming to, and which of those destinations attract the most people traveling on to new places.

Breakthrough
Creating disease-fighting tools with cell-phone mobility data.

Why It Matters
Poor countries lack data-gathering infrastructure; phone data can provide it.

Key Players
- Caroline Buckee, Harvard University
- William Hoffman, World Economic Forum
- Alex Pentland, MIT
- Andy Tatem, University of Southampton

Caroline Buckee, a Harvard epidemiologist, is using detailed data on population movements—gleaned from mobile phones—to build precise new tools for fighting the spread of malaria.

Existing efforts to gather that kind of travel data are spotty at best; sometimes public-health workers literally count people at transportation hubs, Buckee says, or nurses in far-flung clinics ask newly diagnosed malaria victims where they've been recently. "At many border crossings in Africa, they keep little slips of paper—but the slips get lost, and nobody keeps track," she says. "We have abstractions and general models on travel patterns but haven't been able to do this properly—ever."

"This is the future of epidemiology. If we are to eradicate malaria, this is how we will do it."

The data mining will help inform the design of new measures that are likely to include cheap, targeted campaigns of text messages—for example, warning visitors entering the Kericho tower's signal zone to use bed netting. And it will help officials choose where to focus mosquito control efforts in the malarial areas. "You don't want to be spraying every puddle for mosquito larvae all the time. But if you know there is a ton of importation from a certain spot, you want to increase your control program at that spot," Buckee says. "And now I can pinpoint where the importation of a disease is especially important."

Buckee's most recent study, published last year in *Science* and based on records from 15 million Kenyan phones, is a result of a collaboration with her husband, Nathan Eagle, who has been working to make sense of cell-phone data for more than a decade. In the mid-2000s, after getting attention for his work mining data from the phones of volunteers at MIT, Eagle started to get calls from mobile carriers asking for insight into questions like why customers canceled their phone plans. Eagle began working with them. And when the couple spent 18 months in Africa starting in 2006—Buckee was doing work on the genetics of the malaria parasite—he studied call data for various purposes, trying to understand phenomena like ethnic divisions in Nairobi slums and the spread of cholera in Rwanda. Buckee's results show what might be possible when the technology is turned on public-health problems. "This demonstrated 'Yeah, we can really provide not just insight, but actually something that is actionable,'" says Eagle, now CEO of Jana, which runs mobile-phone surveys in the developing world. "This really does work."

That demonstration suggests how such data might be harnessed to build tools that health-care workers, governments, and others can use to detect and monitor epidemics, manage disasters, and optimize transportation systems. Already, similar efforts are being directed toward goals as varied as understanding commuting patterns around Paris and managing festival crowds in Belgium. But mining phone records could be particularly useful in poor regions, where there's often little or no other data-gathering infrastructure. "We are just at the start of using this data for these purposes," says Vincent Blondel, a professor of applied mathematics at the University of Louvain in Belgium and a leading researcher on data gleaned from cell phones. "The exponential adoption of mobile phones in low-income settings—and the new willingness of some carriers to release data—will lead to new technological tools that could change everything."

BLANK SLATE

The world's six billion mobile phones generate huge amounts of data—including location tracking and information on commercial activity, search history, and links in social networks. Innumerable efforts to mine the data in different ways are under way in research and business organizations around the world. And of those six billion

phones, five billion are in developing countries. Many of them are cheap phones that can do little besides make calls and send text messages. But all such activity can be tracked back to cell-phone towers, providing a rough way to trace a person's movements. Throw in the spread of mobile payment technology for simple commerce and you have the raw material for insights not only into epidemiology but into employment trends, social tensions, poverty, transportation, and economic activity.

The prospect of mining data from phones is especially tantalizing in poor countries, where detailed, up-to-date information on these matters has been scarce. "In the developing world, there isn't a functioning census, you don't know where traffic is, you don't always have the data-gathering infrastructure of government," says Alex "Sandy" Pentland, director of the Human Dynamics Lab at MIT, who has long been interested in insights from data created by mobile-phone use. "But all of a sudden, the one thing you do have—cell phones everywhere, especially in the past few years—can give you the equivalent of all that infrastructure already built in the developed world."

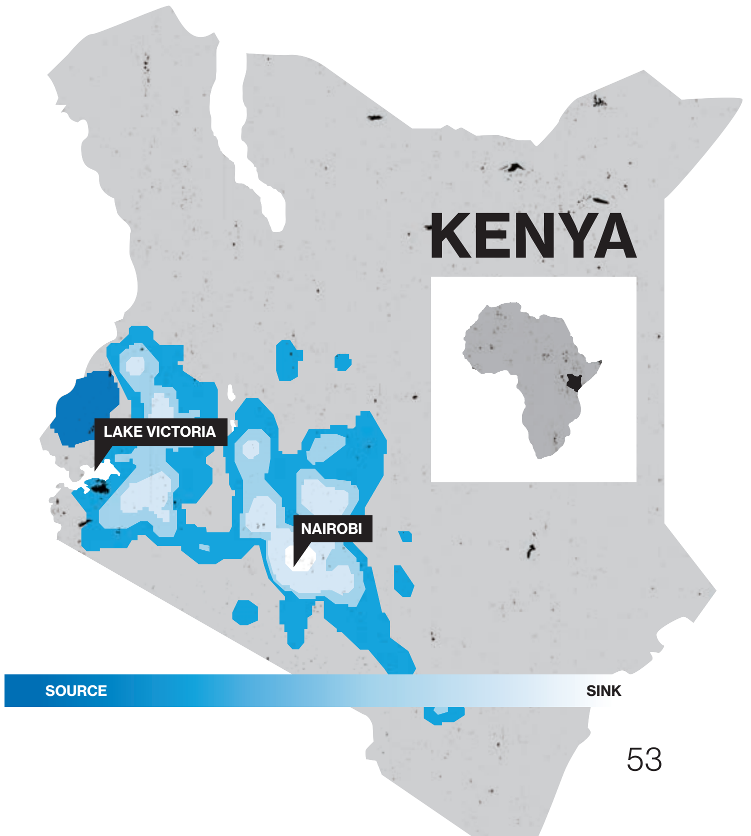
When a call connects to a given base station, that station logs the ID number of the phone and the duration of the call; over time, this information can be used to get a sense of people's regional movements and the shape of their social networks. Purchasing history on phones is also invaluable: records of agricultural purchases could be used to predict food supplies or shortages. And financial data collected by mobile payment systems can build credit histories and help millions of people without access to banking qualify for conventional loans. "The database analysis methods and the computers are very standard," Pentland says. "It's a matter of doing science and finding the right patterns." Certain mobility patterns might relate to the spread of a disease; purchasing patterns could signify that a person has had a change in employment; behavioral changes or movement patterns might relate to the onset of an illness.

A powerful demonstration of how useful data from cheap phones can be came after the January 2010 earthquake in Haiti, which killed more than 200,000 people. Researchers at Sweden's Karolinska Institute obtained data from Digicel, Haiti's largest mobile carrier. They mined the daily movement data from two million phones—from 42 days before the earthquake to 158 days after—and concluded that 630,000 people who had been in Port-au-Prince on the day of the earthquake had left the city within three weeks. They also demonstrated that they could do such calculations in close to real time. They showed—within 12 hours of receiving the data—how many people had fled an area affected by a cholera outbreak, and where they went.

Most important, their work led to a model that could guide responses to future disasters. After analyzing data on pre-earthquake travel habits, the Swedish group found that Haitians generally fled the city for the same places where they'd spent Christmas and New Year's Day. Such findings make it possible to predict where people will go when disaster hits.

SCALING UP

Until recently, these studies were done by researchers who made some special arrangement with carriers to get the data (Eagle obtained it through his academic connections). But last year Orange, the France-based global telecom giant, released to the world's research community—subject to certain conditions and restrictions—data based on 2.5 billion anonymized records from five months' worth of calls made by five million people in Ivory Coast. The first phase of this grand experiment involves seeing just what it's possible to do with the data.



This map, a product of cell-phone data analytics, shows the most important sources of malaria infections (darker shades)—taking into account the potential for further transmission caused by human travel—as well as the major destinations of people exposed to the disease (lighter shades). It can be used to determine where best to focus warnings and mosquito control techniques.

The world's mobile carriers hold a data gold mine, says Nathan Eagle, CEO of Jana, which conducts surveys on mobile phones. But he says widespread use of the data will require new business models and privacy protections.

Nearly a hundred research groups worldwide leaped at the opportunity to analyze the records. The resulting papers were scheduled to be presented in May at a conference at MIT under the name Data for Development, part of a larger conference of data-mining projects in both the poor and rich worlds. "It's the first time a large-scale mobile-phone data set has been released at that scale," says Blondel, who is chairing the conference. The papers had not been formally released at the time of this writing. But one charts social and travel interactions across a traditional north-south ethnic divide, providing insights into how conflict might be averted; another proposes tools for mapping the spread of malaria and detecting disease outbreaks. One corporate lab built a transportation model using cell-phone data to track ridership on 539 buses, 5,000 mini-buses, and 11,000 shared taxis.

Even if the Ivory Coast experiment succeeds, replicating it in other countries may not be easy. Last year the World Economic Forum—the group of leading industry, academic, and political figures who converge annually at Davos, Switzerland—issued a call for governments, development organizations, and companies to develop data analysis tools to improve the lives of people in the poor world. "I shouldn't have to go to operators and say 'I'll do free consulting for you—and in exchange I want to use your data to improve lives,'" Eagle says. "The operators should want to be affiliated with this. Right now many of them don't see the upside, but if we can get world leaders knocking on their doors saying 'Let's do this!' maybe we can get a lot more done."

"We can really provide not just insight, but actually something that is actionable. This really does work."

This will take some careful work to protect privacy and prevent the data from being used in the service of oppression. Orange says it took pains to anonymize its data, but the field needs clear and widely agreed-upon ways to bring the information to market. "There are risks and benefits of having a data-driven society," Pentland says. "There is a question of who owns the data and who controls it. You can imagine what Muammar Qaddafi would have done with this sort of data. Orange is taking the steps to figure out how to create a data commons that induces greater transparency, accountability, and efficiency—to tell where there are unusual events, extreme events, to tell us where the infrastructure is breaking down. There are all sorts of things we can do with it—but it has to be available."

As these larger questions play out, Buckee and Eagle are working on refining and augmenting the data-mining tools in Kenya. Eagle aims to use surveys to sharpen and confirm the picture created by mining cell-phone data on a large scale. Call records alone are often not enough, he says; surveying even a few people could allow researchers to weed out erroneous assumptions about what those records show. Once, while analyzing phone data in Rwanda, Eagle noted that people had not moved around very much after a flood. At first, he theorized that many of them were bedridden with cholera. But it turned out that the flood had washed out the roads.

Buckee hopes to mine phone data to target drug-resistant strains of the malaria parasite. These strains, emerging in Cambodia and elsewhere, could reverse progress against the disease if allowed to proliferate, she warns. So she wants to begin merging data on the parasites' spread into mobility models to help produce targeted disease-fighting strategies. "This is the future of epidemiology," she says. "If we are to eradicate malaria, this is how we will do it." ■

David Talbot is MIT Technology Review*'s chief correspondent.*


HIPOTRONICS
HIPOTRONICS
HIPOTRONICS

COURTESY OF ABB

Supergrids

A high-power circuit breaker could finally make DC power grids practical.

By Kevin Bullis

Breakthrough

Practical high-voltage direct-current circuit breakers.

Why It Matters

DC grids could be far more efficient and make it possible to link widely dispersed wind and solar farms.

Key Players

- ABB
- Siemens
- EPRI
- General Atomics

OPPOSITE: *At ABB's lab in Sweden, equipment such as corona shields—polished disks linked to form spheres (far left)—are used to test a high-voltage DC circuit breaker.* **ABOVE:** *A simulation center develops controls for DC grids.* **BELOW:** *ABB workers at a DC-to-AC conversion station.*

High-voltage DC power lines can efficiently transport electricity over thousands of kilometers and for long distances underwater, outperforming the AC lines that dominate transmission grids now. But for a century, AC prevailed because high-voltage DC could be used only for point-to-point transmission, not to form the integrated grid networks needed for a stable electricity system.

The Swiss conglomerate ABB has solved the main technical hurdle to such grids. It has developed a practical high-voltage DC circuit breaker that disconnects parts of the grid that have a problem, allowing the rest to keep working.

DC grids would be more efficient at connecting far-flung sources of renewable energy, allowing utilities to average out local variations in wind and solar power while bringing power to areas without much sunshine or wind. Solar power from the Sahara could power cloudy Germany, and wind power from all over Europe could keep the lights on at night. The result: more reliable renewable energy that can better compete with fossil fuels. ■

Additive Manufacturing

GE, the world's largest manufacturer, is on the verge of using 3-D printing to make jet parts.

By Martin LaMonica
Photograph by Jennifer May

Breakthrough

GE will use 3-D printing to produce a key metal part for its new jet engines.

Why It Matters

Because it can potentially make complex parts more cheaply, additive manufacturing could revitalize many advanced manufacturing sectors.

Key Players

- GE Aviation
- EADS
- United Technologies
- Pratt & Whitney

General Electric is making a radical departure from the way it has traditionally manufactured things. Its aviation division, the world's largest supplier of jet engines, is preparing to produce a fuel nozzle for a new aircraft engine by printing the part with lasers rather than casting and welding the metal. The technique, known as additive manufacturing (because it builds an object by adding ultrathin layers of material one by one), could transform how GE designs and makes many of the complex parts that go into everything from gas turbines to ultrasound machines.

Additive manufacturing—the industrial version of 3-D printing—is already used to make some niche items, such as medical implants, and to produce plastic prototypes for engineers and designers. But the decision to mass-produce a critical metal-alloy part to be used in thousands of jet engines is a significant milestone for the technology. And while 3-D printing for consumers and small entrepreneurs has received a great deal of publicity, it is in manufacturing where the technology could have its most significant commercial impact (see "The Difference Between Makers and Manufacturers," January/February 2013).

Last fall, GE purchased a pair of companies with know-how in automated precision manufacturing of metals and then folded the technology into the operations of GE Aviation. That group doesn't have much time to demonstrate that its new technology can work at scale. CFM International, GE's joint venture with France's Snecma, will use the 3-D-printed nozzles in its LEAP jet engine, due to go into planes in late 2015 or early 2016 (CFM says it already has commitments of $22 billion). Each engine will use 10 to 20 nozzles; GE needs to make 25,000 of the nozzles annually within three years.

GE chose the additive process for manufacturing the nozzles because it uses less material than conventional techniques. That reduces GE's production costs and, because it makes the parts lighter, yields significant fuel savings for airlines. Conventional techniques would require welding about 20 small pieces together, a labor-intensive process in which a high percentage of the material ends up being scrapped. Instead, the part will be built from a bed of cobalt-chromium powder. A computer-controlled laser shoots pinpoint beams onto the bed to melt the metal alloy in the desired areas, creating 20-micrometer-thick layers one by one. The process is a faster way to make complex shapes because the machines can run around the clock. And additive manufacturing in general conserves material because the printer can handle shapes that eliminate unnecessary bulk and create them without the typical waste.

The rest of GE—together with its competitors—is watching closely. GE Power & Water, which makes large gas and wind turbines, has already identified parts it can make with the additive process, and GE Healthcare has developed a method to print transducers, the expensive ceramic probes used in ultrasound machines. "It's really fundamentally changing the way we think about the company," says Mark Little, GE's chief technology officer.

Breaking with traditional manufacturing techniques, such as casting and machining material, gives GE product designers far greater flexibility. Additive manufacturing machines work directly from a computer model, so people can devise completely new shapes without regard for existing manufacturing limitations. "We can make configurations that we just couldn't before," Little says.

GE engineers are starting to explore how to use additive manufacturing with a wider range of metal alloys, including some materials specifically designed for 3-D printing. GE Aviation, for one, is looking to use titanium, aluminum, and nickel-chromium alloys. A single part could be made of multiple alloys, letting designers tailor its material characteristics in a way that's not possible with casting. A blade for an engine or turbine, for example, could be made with different materials so that one end is optimized for strength and the other for heat resistance.

All that is still on paper—or rather, in the computerized designs of product engineers. For now, GE's engine nozzle—a part small enough to fit in the palm of your hand—will be the first big test of whether additive manufacturing can revolutionize the way complex high-performance products are made. T

Prototypes of brackets for airplane engines show how additive manufacturing can produce complex, precisely designed shapes like the one at right.

Martin LaMonica is a contributing editor at MIT Technology Review.


16:01
Incoming Call
Jane Pebble
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New Message
@techreview
@pebble: A Transitional Form of #Wearable Computer - MIT
three fifty one
51

Smart Watches

The designers of the Pebble watch realized that a mobile phone is more useful if you don't have to take it out of your pocket.

By John Pavlus
Photographs by Peter Belanger

Eric Migicovsky didn't really want a "wearable computer." When he first conceived of what would become the Pebble smart watch five years ago, as an industrial-design student at Delft University of Technology in the Netherlands, he just wanted a way to use his smartphone without crashing his bicycle. "I thought of creating a watch that could grab information from my phone," the 26-year-old Canadian says. "I ended up building a prototype in my dorm room."

Now Migicovsky is shipping 85,000 Pebble watches to eager customers who don't want to lug a glass slab out of their pocket just to check their e-mail or the weather forecast. Pebble uses Bluetooth to connect wirelessly to an iPhone or Android phone and displays notifications, messages, and other simple data of the user's choosing on its small black-and-white LCD screen. In April 2012, using the online fund-raising platform Kickstarter, Migicovsky asked for $100,000 to help bring Pebble to market. Five weeks later, he had more than $10 million—making his the highest-grossing Kickstarter campaign yet. Suddenly smart watches are a real product category: Sony entered the market last year, Samsung is about to, and Apple seems likely to follow.

Breakthrough
Watches that pull selected data from mobile phones so their wearers can absorb information with a mere glance.

Why It Matters
Even as computing gets more sophisticated, people want simple and easy-to-use interfaces.

Key Players
- Pebble
- Sony
- Motorola
- MetaWatch

Although the $150 Pebble watch can be used to control a music playlist or run simple apps like RunKeeper, a cloud-based fitness tracker, Migicovsky and his team purposely designed the watch to do as little as possible, leaving more complicated apps for phones. This emphasis on making the watch "glanceable" informed nearly every aspect of the design. The black-and-white screen, for example, can be read in direct sunlight and displays content persistently without needing to "sleep" to conserve battery power, as color or touch-screen displays do.

These watches are coming to market a few months before Google Glass, which is another attempt to solve the problem Pebble addresses—namely, that "interacting with our phones has a certain overhead that doesn't need to be there," says Mark Rolston, chief creative officer of Frog Design. But Google Glass will try to replace the smartphone altogether by combining a computer and monitor into eyeglass frames so that wearers can "augment" their view of the world with data. That lines up with predictions about the advent of wearable computing, but it's easy to see Pebble's idea being much more popular. By making use of a watch—a classic accessory—Pebble is trying to fit in to long-standing social norms rather than create new ones.

Memory Implants

A maverick neuroscientist believes he has deciphered the code by which the brain forms long-term memories.

Next: testing a prosthetic implant for people suffering from memory loss.

By Jon Cohen
Illustration by Dan Winters

Breakthrough
Animal experiments show it is possible to correct for memory problems with implanted electrodes.

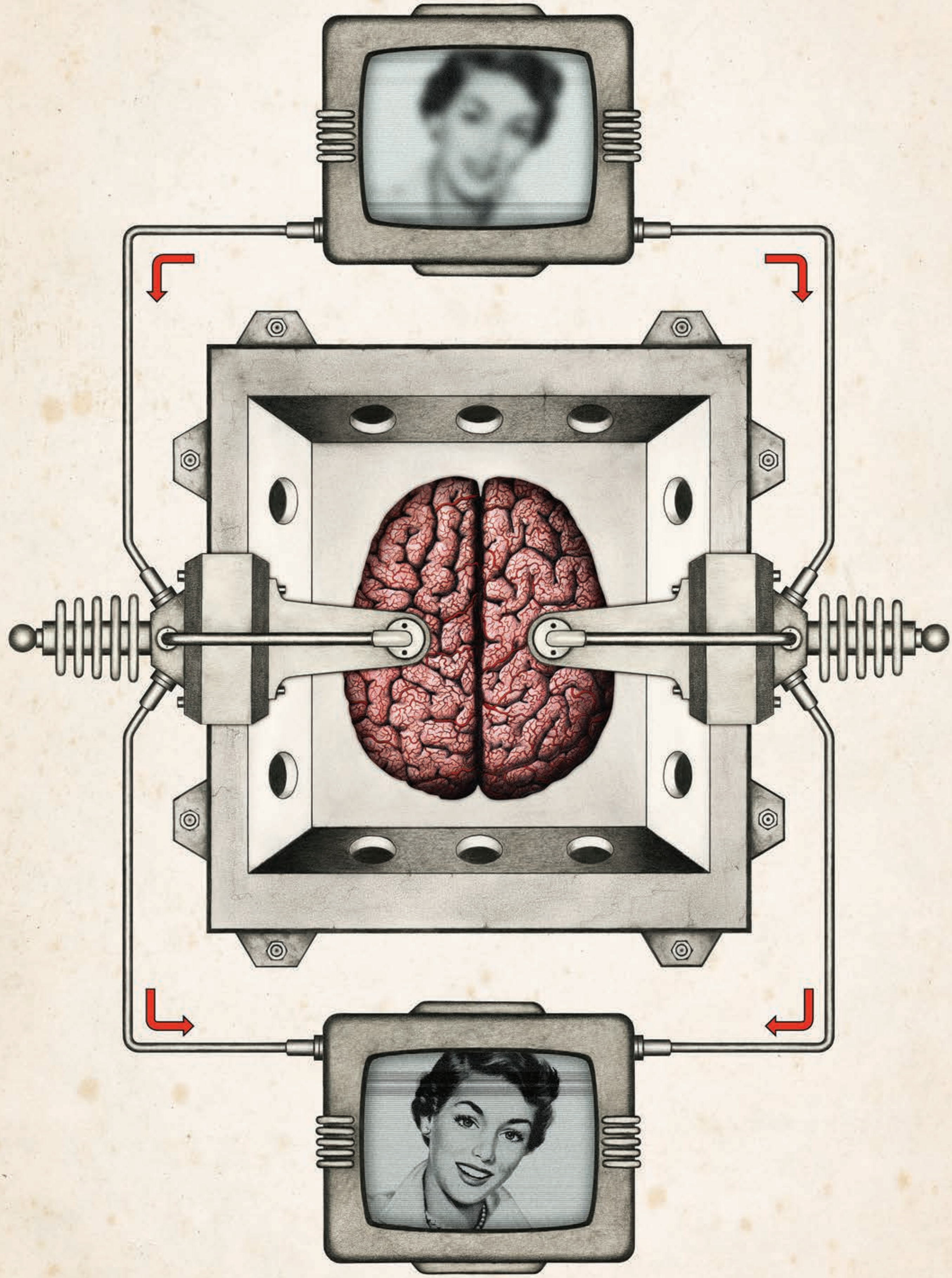
Why It Matters
Brain damage can cause people to lose the ability to form long-term memories.

Key Players
- Theodore Berger, USC
- Sam Deadwyler, Wake Forest
- Greg Gerhardt, University of Kentucky
- DARPA

Theodore Berger, a biomedical engineer and neuroscientist at the University of Southern California in Los Angeles, envisions a day in the not too distant future when a patient with severe memory loss can get help from an electronic implant. In people whose brains have suffered damage from Alzheimer's, stroke, or injury, disrupted neuronal networks often prevent long-term memories from forming. For more than two decades, Berger has designed silicon chips to mimic the signal processing that those neurons do when they're functioning properly—the work that allows us to recall experiences and knowledge for more than a minute. Ultimately, Berger wants to restore the ability to create long-term memories by implanting chips like these in the brain.

The idea is so audacious and so far outside the mainstream of neuroscience that many of his colleagues, says Berger, think of him as being just this side of crazy. "They told me I was nuts a long time ago," he says with a laugh, sitting in a conference room that abuts one of his labs. But given the success of recent experiments carried out by his group and several close collaborators, Berger is shedding the loony label and increasingly taking on the role of a visionary pioneer.

Berger and his research partners have yet to conduct human tests of their neural prostheses, but their experiments show how a silicon chip externally connected



to rat and monkey brains by electrodes can process information just like actual neurons. "We're not putting individual memories back into the brain," he says. "We're putting in the capacity to generate memories." In an impressive experiment published last fall, Berger and his coworkers demonstrated that they could also help monkeys retrieve long-term memories from a part of the brain that stores them.

If a memory implant sounds far-fetched, Berger points to other recent successes in neuroprosthetics. Cochlear implants now help more than 200,000 deaf people hear by converting sound into electrical signals and sending them to the auditory nerve. Meanwhile, early experiments have shown that implanted electrodes can allow paralyzed people to move robotic arms with their thoughts. Other researchers have had preliminary success with artificial retinas in blind people.

Still, restoring a form of cognition in the brain is far more difficult than any of those achievements. Berger has spent much of the past 35 years trying to understand fundamental questions about the behavior of neurons in the hippocampus, a part of the brain known to be involved in forming memory. "It's very clear," he says. "The hippocampus makes short-term memories into long-term memories."

What has been anything but clear is how the hippocampus accomplishes this complicated feat. Berger has developed mathematical theorems that describe how electrical signals move through the neurons of the hippocampus to form a long-term memory, and he has proved that his equations match reality. "You don't have to do everything the brain does, but can you mimic at least some of the things the real brain does?" he asks. "Can you model it and put it into a device? Can you get that device to work in any brain? It's those three things that lead people to think I'm crazy. They just think it's too hard."

Cracking the Code

Berger often speaks in sentences that stretch to paragraph length and have many asides, footnotes, and complete diversions from the point. I ask him to define memory. "It's a series of electrical pulses over time that are generated by a given number of neurons," he says. "That's important because you can reduce it to this and put it back into a framework. Not only can you understand it in terms of the biological events that happened; that means that you can poke it, you can deal with it, you can put an electrode in there, and you can record something that matches your definition of a memory. You can find the 2,147 neurons that are part of this memory. And what do they generate? They generate this series of pulses. It's not bizarre. It's something you can handle. It's useful. It's what happens."

This is the conventional view of memory, but it only scratches the surface. And to Berger's perpetual frustration, many colleagues who probe this mysterious realm of the brain haven't attempted to go much deeper. Neuroscientists track electrical signals in the brain by monitoring action potentials, microvolt changes on the surfaces of neurons. But all too often, says Berger, their reports oversimplify what's actually taking place. "They find an important event in the environment and count action potentials," he says. "They say, 'It went up from 1 to 200 after I did something. I'm finding something interesting.' What are you finding? 'Activity went up.' *But what are you finding*? 'Activity went up.' So what? Is it coding something? Is it representing something that the next neuron cares about? Does it make the next neuron do something different? That's what we're supposed to be doing: explaining things, not just describing things."

Berger takes a marker and fills a whiteboard from top to bottom with a line of circles that represent neurons. Next to each one, he draws a horizontal line that has a different pattern of blips on it. "This is you in my brain," he says. "My hippocampus has already formed a long-term memory of you. I'll remember you into next week. But how can I distinguish you from the next person? Let's say there are 500,000 cells in the hippocampus that represent you, and there are all sorts of things that each cell is coding—like how your nose is relative to your eyebrow—and they code that with different patterns. So the reality of the nervous system is really complicated, which is why we're still asking such basic, limited questions about it."

In graduate school at Harvard, Berger's mentor was Richard Thompson, who studied localized, learning-induced changes in the brain. Thompson used a tone and a puff of air to condition rabbits to blink their eyes, aiming to determine *where* the memory he induced was stored. The idea was to find a specific place in the brain where the learning was localized, says Berger: "If the animal did learn and you removed it, the animal couldn't remember."

Thompson, with Berger's help, managed to do just that; they published the results in 1976. To find the site in the rab-

If one neuron fires at a specific time and place, what exactly do the neighboring neurons do in response?

Theodore Berger has spent his career trying to understand how neurons form memories.

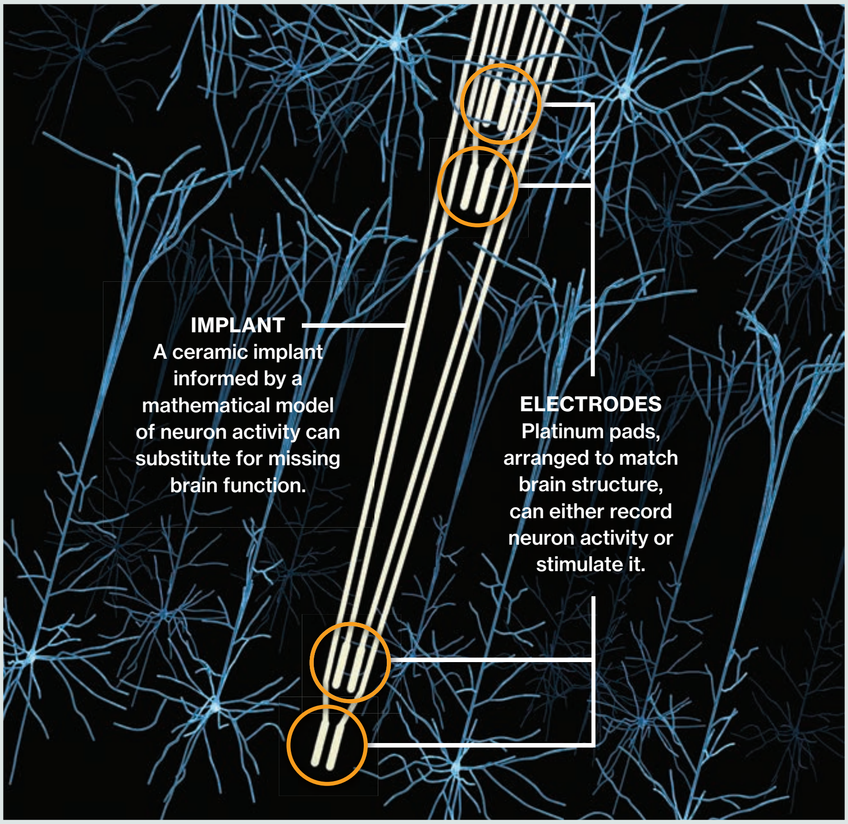
bits, they equipped the animals' brains with electrodes that could monitor the activity of a neuron. Neurons have gates on their membranes, which let electrically charged particles like sodium and potassium in and out. Thompson and Berger documented the electrical spikes seen in the hippocampus as rabbits developed a memory. Both the spikes' amplitude (representing the action potential) and their spacing formed patterns. It can't be an accident, Berger thought, that cells fire in a way that forms patterns with respect to time.

This led him to a central question that underlies his current work: as cells receive and send electrical signals, what pattern describes the quantitative relationship between the input and the output? That is, if one neuron fires at a specific time and place, what exactly do the neighboring neurons do in response? The answer could reveal the code that neurons use to form a long-term memory.

But it soon became clear that the answer was extremely complex. In the late 1980s, Berger, working at the University of Pittsburgh with Robert Sclabassi, became fascinated by a property of the neuronal network in the hippocampus. When they stimulated the hippocampus of a rabbit with electrical pulses (the input) and charted how signals moved through different populations of neurons (the output), the relationship they observed between the two wasn't linear. "Let's say you put in 1 and get 2," says Berger. "That's pretty easy. It's a linear relation." It turns out, however, that there's "essentially no condition in the brain where you get linear activity, a linear summation," he says. "It's always nonlinear." Signals overlap, with some suppressing an incoming pulse and some accentuating it.

By the early 1990s, his understanding—and computing hardware—had advanced to the point that he could work with his colleagues at the University of Southern California's department of engineering to make computer chips that mimic the signal processing done in parts of the hippocampus. "It became obvious that if I could get this stuff to work in large numbers in hardware, you've got part of

Portrait by Misha Gravenor



Regaining Lost Brain Function

How do you make an electronic brain prosthesis that could restore a person's ability to form long-term memories? Recent experiments by Theodore Berger and his colleagues, including Sam Deadwyler at Wake Forest Baptist Medical Center in Winston-Salem, North Carolina, and researchers at the University of Kentucky in Lexington, have begun to describe how it might be done.

Last year, the team showed that an implant that records the activity of one set of neurons and directs the activity of another can replace lost brain function in monkeys. The researchers used an array of electrodes to measure the electrical activity of neurons in the animals' prefrontal cortex, a brain region involved in decision making that directs many types of cognitive responses associated with memory. Five monkeys were trained to perform a memory task in which they were shown an image on a screen and then had to use hand movements to steer a cursor to that image when they were subsequently shown a collection of clip-art pictures.

The monkeys' neural activity was recorded by a tiny ceramic-enclosed electronic device and relayed to an external computer. In the first part of the experiment, the researchers analyzed the brain activity they had recorded from the cortex. But then came the hard part. Memory is formed when one set of neurons processes the signals from another set, but how can you replicate this processing in an electronic device? First, you have to figure out the code the brain is using. From the initial recordings, the research team was able to extrapolate what's called a MIMO model—short for multi-input/multi-output. This type of mathematical model can characterize the neural firing patterns detected by the electrode implant and, after processing the patterns, spit out the signals that instruct other neurons to form the appropriate memory.

To demonstrate that their model worked, the researchers gave the monkeys cocaine. The cocaine-addled monkeys had trouble remembering the correct image. But with the implant in place and the MIMO model translating the incoming signals and feeding data back to another set of neurons, they were able to pick out the right picture about as reliably as usual, if not slightly more so.

But how could a doctor replace a brain function, such as the ability to form long-term memories, that someone had already lost? In that case, it wouldn't be possible to simply mimic a previous example of how the individual's brain worked and duplicate it in the electronic device. However, preliminary work suggests that a recording from a healthy person's brain could be used in the injured or sick. "We've recorded from a number of rodents and were able to derive a generic model for certain kinds of processing," says Deadwyler. The research team will need to see if the same rules apply to primates. If they do, it might mean that a MIMO model could be used to form "a generic pattern that would resemble the kind of processing most of us do with respect to certain kinds of tasks," says Deadwyler. *—Susan Young*

Graphic by John MacNeill

the brain," he says. "Why not hook up to what's existing in the brain? So I started thinking seriously about prosthetics long before anybody even considered it."

A Brain Implant

Berger began working with Vasilis Marmarelis, a biomedical engineer at USC, to begin making a brain prosthesis (see "Regaining Lost Brain Function," left). They first worked with hippocampal slices from rats. Knowing that neuronal signals move from one end of the hippocampus to the other, the researchers sent random pulses into the hippocampus, recorded the signals at various locales to see how they were transformed, and then derived mathematical equations describing the transformations. They implemented those equations in computer chips.

Next, to assess whether such a chip could serve as a prosthesis for a damage hippocampal region, the researchers investigated whether they could bypass a central component of the pathway in the brain slices. Electrodes placed in the region carried electrical pulses to an external chip, which performed the transformations normally done in the hippocampus. Other electrodes delivered the signals back to the slice of brain.

Then the researchers took a leap forward by trying this in live rats, showing that a computer could in fact serve as an artificial component of the hippocampus. They began by training the animals to push one of two levers to receive a treat, recording the series of pulses in the hippocampus as they chose the correct one. Using those data, Berger and his team modeled the way the signals were transformed as the lesson was converted into a long-term memory, and they captured the code believed to represent the memory itself. They proved that their device could generate this long-term memory code from input signals recorded in rats' brains while they learned the task. Then they gave the rats a drug that interfered with their ability to form long-term memories, causing them to forget which lever produced the treat. When the researchers pulsed the drugged rats' brains with the code, the animals were again able to choose the right lever.

Last year, the scientists published primate experiments involving the prefrontal cortex, a part of the brain that retrieves the long-term memories created by the hippocampus. They placed electrodes in the monkey brains to capture the code formed in the prefrontal cortex that they believed allowed the animals to remember an image they had been shown earlier. Then they drugged the monkeys with cocaine, which impairs that part of the brain. Using the implanted electrodes to send the correct code to the monkeys' prefrontal cortex, the researchers significantly improved the animal's performance on the image-identification task.

Within the next two years, Berger and his colleagues hope to implant an actual memory prosthesis in animals. They also want to show that their hippocampal chips can form long-term memories in many different behavioral situations. These chips, after all, rely on mathematical equations derived from the researchers' own experiments. It could be that the researchers were simply figuring out the codes associated with those specific tasks. What if these codes are not generalizable, and different inputs are processed in various ways? In other words, it is possible that they haven't cracked the code but have merely deciphered a few simple messages.

Berger allows that this may well be the case, and his chips may form long-term memories in only a limited number of situations. But he notes that the morphology and biophysics of the brain constrain what it can do: in practice, there are only so many ways that electrical signals in the hippocampus can be transformed. "I do think we're going to find a model that's pretty good for a lot of conditions and maybe most conditions," he says. "The goal is to improve the quality of life for somebody who has a severe memory deficit. If I can give them the ability to form new long-term memories for half the conditions that most people live in, I'll be happy as hell, and so will be most patients."

Despite the uncertainties, Berger and his colleagues are planning human studies. He is collaborating with clinicians at his university who are testing the use of electrodes implanted on each side of the hippocampus to detect and prevent seizures in patients with severe epilepsy. If the project moves forward as envisioned, Berger's group will piggyback on the trial to look for memory codes in those patients' brains.

"I never thought I'd see this go into humans, and now our discussions are about when and how. I never thought I'd live to see the day."

"I never thought I'd see this go into humans, and now our discussions are about when and how," he says. "I never thought I'd live to see the day, but now I think I will."

Jon Cohen is a freelance writer and a contributing editor at MIT Technology Review.

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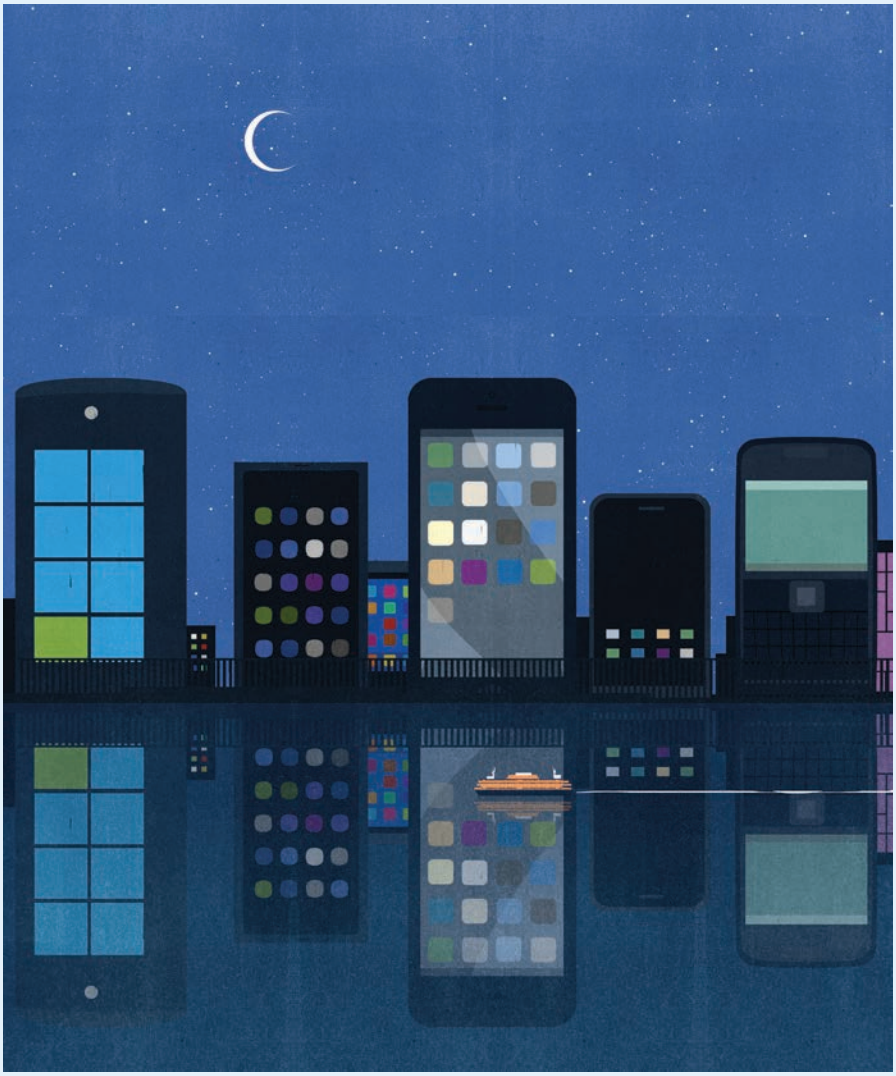
Additional stories include "Qualcomm Wants to Be Famous," "For Investors, Mobile Startup Boom Gives Way to Caution," "Akamai's Plan for a Wireless Data Fast Lane," and more.

A BUSINESS REPORT ON

Making Money in Mobile

Mobile computing is the fastest-spreading consumer technology in history. But 65 percent of the world isn't even online. That means the real change is only beginning.



SHOUT

The Big Question

Mobile Computing Is Just Getting Started

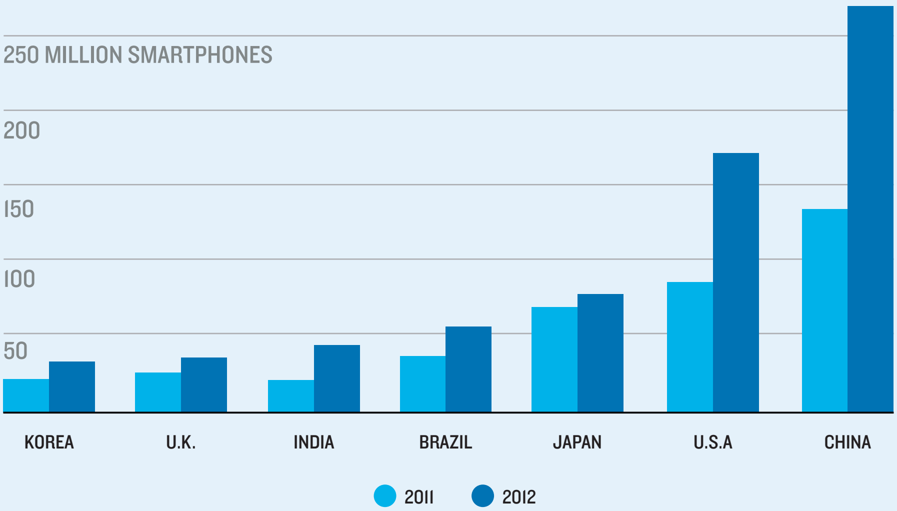
Smartphones, tablets, and wireless data plans are already a trillion-dollar business.

● Mobile computers are spreading faster than any other consumer technology in history. In the United States, smartphones have even begun reaching the group of relative technophobes that consumer researchers call the "late majority." About half of mobile-phone users now have one.

The big question facing technology companies, and the subject of this month's *MIT Technology Review Business Report*, is how to make money from this rapidly expanding technology.

Wireless carriers make money at the greatest scale. Globally, 900 of them take in $1.3 trillion in revenue each year, about four times the combined revenue of Google, Apple, Microsoft, and →

More to Grow
The world's seven largest markets for smartphone subscriptions



SOURCE: KPCB, MORGAN STANLEY

Intel. Yet individual device makers, notably Apple, capture more profit. That company's markets aren't restricted to one network. Its products, by bringing personal computing to phones, have sharply increased their capabilities and value.

In 2007, the average wholesale price of a mobile phone was $120 and falling; analysts talked of market saturation because nearly everyone who could afford one had one. But since then, prices have leapt by 50 percent, and the revenue from all mobile handset sales has doubled.

Apps and services still account for the least amount of money in mobile computing. Mobile advertising brings in only $9

23%
Facebook's share of the time U.S. smartphone users spent on apps.

billion as yet. But here is where the most opportunities lie. Facebook has a monthly audience as large as any that's ever been reached. And in January, it said for the first time that most of that audience was coming from mobile devices.

The swings in the company's value—it was worth $104 billion at its IPO, then $42 billion, and now more than $60 billion—are a measure of its No. 1 ranking among apps (23 percent of the time that Americans spend on mobile apps is devoted to Facebook) and the uncertainty about whether Facebook can profit from ads on the small screen, something it has recently started to do.

Who isn't making money is a story too. For example, Microsoft's share of mobile computing is negligible. The company "didn't miss cell phones," Bill Gates said in a TV interview in February, "but the way we went about it didn't allow us to get the leadership. It was clearly a mistake." Gates underplayed what's been lost. In 2009, his company's software was on 90 percent of personal computing devices, counting smartphones, tablets, and PCs. At the end of 2012, it was on just 23 percent of such devices.

That was fast. Now, watching the fever lines on tech analysts' charts cross and collide has become a spectator sport. Smartphones outsell PCs. Touch screens outnumber keyboards. Even ordinary search—Google's great cash cow—is declining in the United States as people use their phones to search for restaurants, bus times, and weather reports.

Large companies are responding with bold moves. Google is developing Google Glass—a computer in a pair of glasses. The components are cheap, off-the-shelf. It's not hard to make. Google hopes this new way to use a computer tilts mobile revenue in its direction. Whether anyone will want Glass isn't clear, but it's worth trying. That's because we're still early in the mobile switchover.

How early? Mary Meeker, the Internet prognosticator, leads her annual set of predictions with observations on the underlying trends. By her tally, 1.14 billion people own mobile computers, but another 5.8 billion don't. Of those, 4.5 billion aren't users of the Internet at all.

One entrepreneur with a feel for the opportunities in those figures is Suneet Singh Tuli. His company, DataWind, is trying to sell dirt-cheap tablets in India. Just as customers in the developing world skipped landlines for cell phones, Tuli thinks, they'll skip PCs for wireless tablets and smartphones. It makes sense: in India only 11 percent of people are on the Internet, but just about everyone already has a mobile phone. "We're talking about what will be their first computer," he says.

That's a reminder of what the real stakes are: the killer app isn't Angry Birds but access to computing itself. Wireless smartphones and tablets allow the Internet and its digital affordances to flow into every hand, everywhere, in every circumstance. We're not in the "late majority" yet, either. We've got nearly six billion people to go.

—Antonio Regalado

Emerged Technologies

Google Wants to Install a Computer on Your Face

The search company is developing a computer in a pair of glasses. But why would anyone wear them?

● Google Glass, a compact computer fitted onto a pair of slim metal eyeglass frames, must be considered an impres-

sive technical achievement. But can it become a business?

Glass is the pet project of Google's cofounder Sergey Brin. The compact frames have a boom on one side that hides a camera, a battery, motion sensors, a wireless connection to reach the Internet, and other electronics. That boom also contains a small display, the light from which is directed into a person's eye by a thumb-size prism positioned just under his or her right eyebrow.

Google has shown off video and crisp photos captured by trapeze artists, skydivers, and supermodels wearing Glass prototypes like those it first unveiled in April 2012. Recently the company posted a show reel in which people used voice commands to order Glass to take images and send messages.

But just how this R&D project might become a popular product and a significant contributor to Google's bottom line remains fuzzy.

Clearly, anyone who can reinvent the mobile computing experience has everything to gain. Apple proved that with its iPhone and tablets. Yet for Google to turn Glass into a similar commercial coup, the company will have to negotiate challenges in fashion, design, and human relationships that lie outside its previous experience. Google, which says it plans to start selling Glass this year, declined to comment for this article.

Making Glass affordable to consumers will be the easiest part. The device may look unique, but it will mostly be a remix of compact electronic components now standard in smartphones, and it should cost about as much as a smartphone to make.

"We put the average prices of smart glasses, not just Google's, at $400," says Theo Ahadome, an analyst with IHS Insight, which strips down phones, tablets, and other devices to estimate the cost of manufacturing them.

Persuading large numbers of people to put the device on their faces will be a far bigger challenge. Blake Kuwahara, an eyewear designer who has created glasses for Carolina Herrera and other fashion houses, says Google will have to reinvent its product to succeed as fashion, not just a computer for your face.

To judge from Google's prototypes, "it's clear that this device was designed by industrial designers," says Kuwahara. "To make this something that someone will want to wear full time, there need to be adjustments to the aesthetics and styling—it reads as a device and not a pair of fashion eyewear."

It also remains unclear what Glass's killer app will be. Google has floated some ideas—people could use the technology to get directions while traveling, or to share video of experiences such as roller-coaster rides with friends in real time. Those videos make for great TV coverage of Google's prototype, but the value to most people is uncertain, since most everything you can do with Glass you can do with a smartphone, and probably more easily.

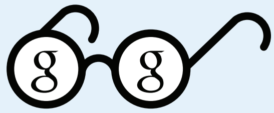
Perhaps recognizing the dilemma, Brin has openly sought help generating more ideas for how to use the product, and he's also taken digs at the competition. During the TED conference in late February, he called smartphones "emasculating" because their users are "hunched up, looking down, rubbing a featureless piece of glass." By contrast, Glass would "free your eyes," he said.

Last June, Brin appealed to software engineers attending Google's annual conference for outside developers, inviting them to pay $1,500 for prototypes to experiment with (these early "Explorer" models have yet to ship). After signing nondisclosure agreements, some developers attended closed-door meetings last month in San Francisco and New York to get their first experience with the new technology.

Hardly any software programmers have experience developing for something like Google Glass, and doing it well will require throwing out some fundamental conventions of today's computers, says Mark Rolston, chief creative officer at Frog Design, a design firm that has worked with many consumer technology companies.

Today, people treat mobile computers like tool boxes, says Rolston, digging out individual tools—applications—to achieve particular tasks. "If you're wearing a computer, that application model needs to go away," he says. "Instead, it needs to be cued by the outside world so it feels like natural life, not interacting with a computer."

Google's limited demonstrations of Glass suggest that the company agrees. The glasses do have a touch pad on the side for scrolling through menus, but in Google's demonstrations, users are shown calling out "Okay, Glass" and then saying a command such as "Take a picture." Google's Android mobile operating system for smartphones has also been shifting away from an app-centric approach. Google Now, a core feature of the latest version of Android, offers live arrival and departure times when a person is near a transit stop, an approach well suited to Glass.



$400

Estimated retail price of smart glasses

Those same techniques may also be suited to mixing in targeted ads, although the leader of the Glass project, Babak Parviz, said in January that he had no plans for ads to appear on the device.

The least predictable part of Google's task is to make Glass as acceptable to people who aren't wearing it as it is to those who are. Looks aside, the way people wearing Glass behave will be crucial, says Rolston. For example, talking with or even paying attention to other people while information streams directly into your field of view could be challenging.

"We'll have to learn the social boundaries [of] ignoring someone when it looks like you're engaged," says Rolston. "Normal cues like taking out your phone will go away."

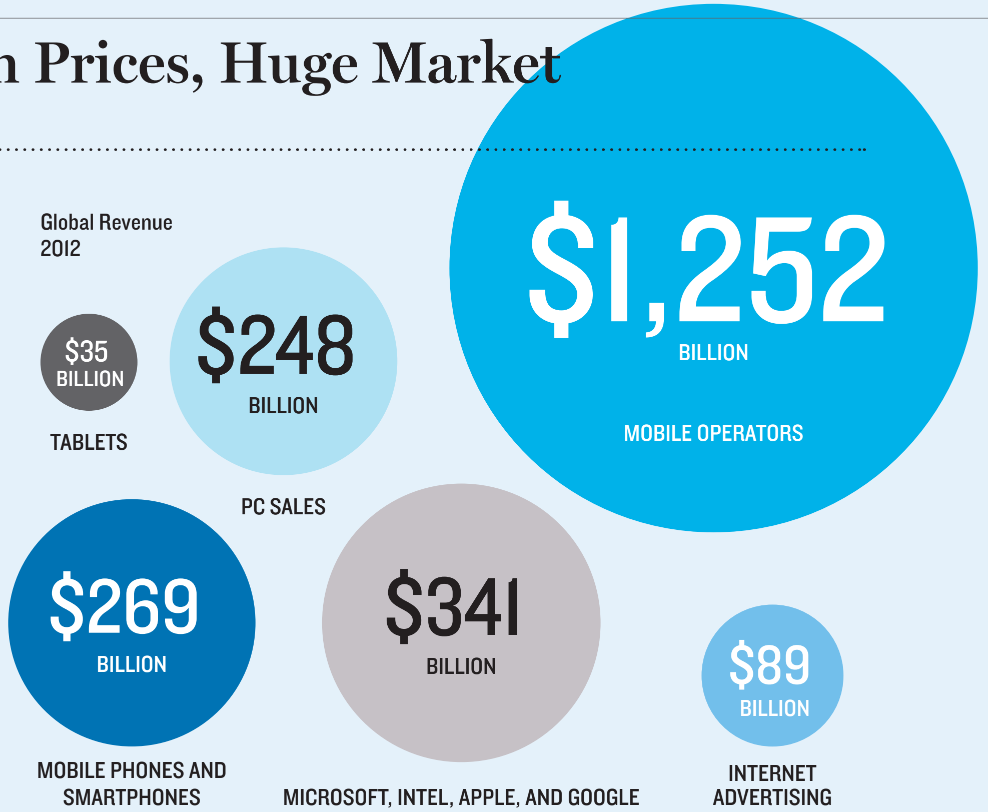
—Tom Simonite

by Benedict Evans

Smartphones: High Prices, Huge Market

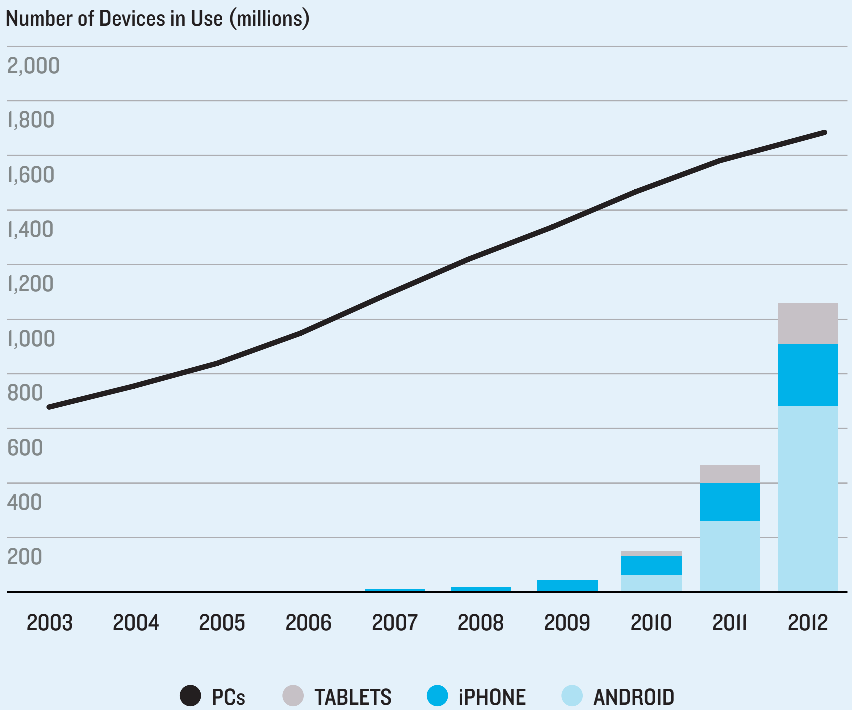
TALE OF TWO INDUSTRIES

Smartphones have created a bridge between two previously separate industries: wireless networks and personal computing. For Internet firms and device makers, this means access to the world's largest network of people. As can be seen at right, the wireless telephone business is much larger than personal computing. In 2012, the world's mobile operators did $1.2 trillion in business and served around 3.2 billion people, versus perhaps 1.7 billion people who used PCs to access the Internet. By comparison, the combined revenue of Microsoft, Google, Intel, Apple, and the entire global PC industry was $590 billion. Online advertising, the main driver of the consumer Internet, generated only $89 billion in revenue.



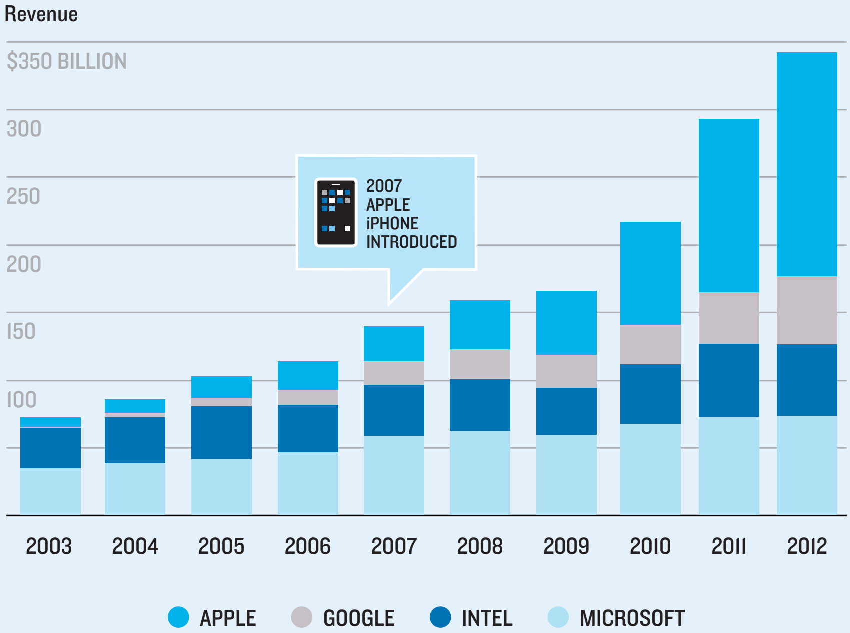
SHIFT AWAY FROM PCs

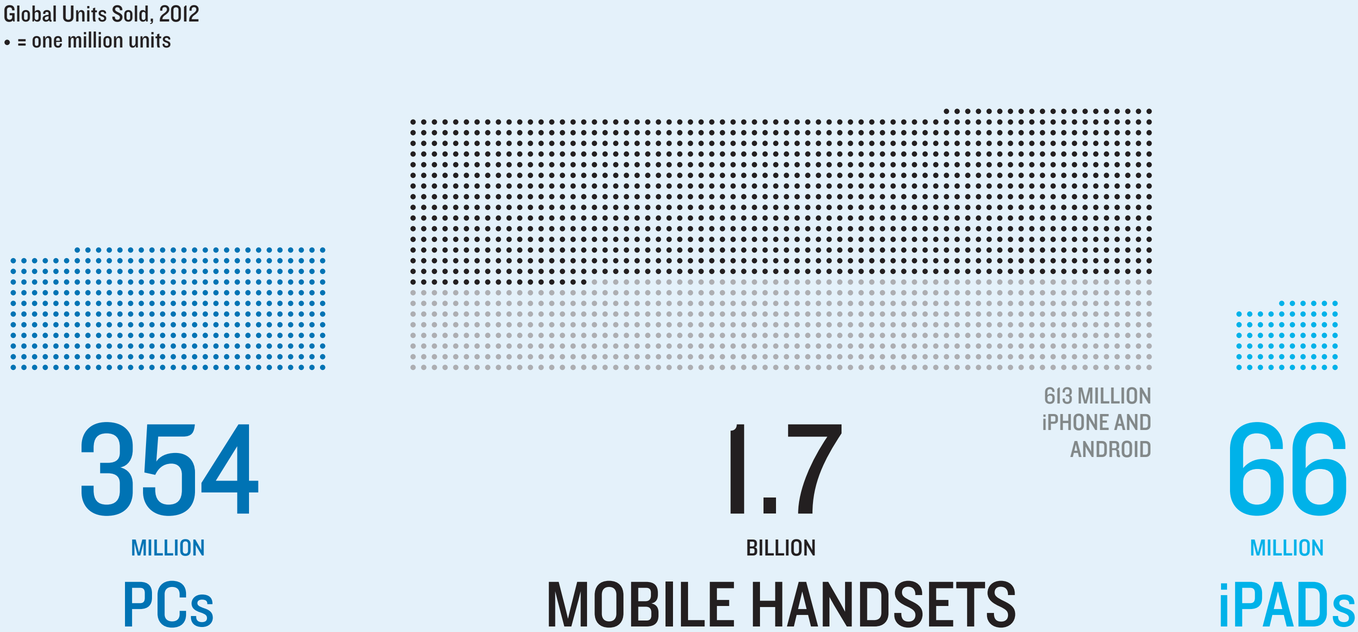
PCs still represent a majority of personal computing devices in use globally. But not for long. As sales of smartphones and tablets increase rapidly, they are becoming the dominant personal-computing paradigm. At right are the number of PCs, tablets, and smartphones in use, as well as (far right) the number of each sold in 2012. Growth in smartphone sales is coming largely at the expense of older-style "feature phones" as people replace them. As the data show, two-thirds of mobile-phone purchasers have yet to convert to smartphones. Close to a billion smartphones will be sold in 2013, while PC sales will gradually decline.



iPHONE'S PRICE

Smartphones have greatly increased the profitability of the mobile-phone handset business. The average selling price of all mobile phones rose from about $105 in 2010 to $180 at the end of 2012, largely thanks to Apple's iPhone. In 2012, Apple sold 136 million iPhones for $85 billion, averaging $629 per phone. By comparison, the average selling price of a PC is about $700. With a further $33 billion in revenue from iPads, Apple's annual revenue now exceeds the combined business of Intel and Microsoft. Sales by other companies of Android smartphones (not shown) reached 480 million units in 2012, generating an estimated $120 billion in revenue at an average selling price of $250.





Case Studies

Here's Where They Make China's Cheap Smartphones

Apple and Samsung, beware. Practically anyone can make a smartphone these days.

● A little over a year ago, 38-year-old entrepreneur Liang Liwan wasn't making smartphones at all. This year, he expects to build 10 million of them.

Liang's company, Xunrui Communications, buys smartphone components and then feeds them to several small factories around Shenzhen, in southern China. There, deft-fingered workers assemble the parts into basic smartphones that retail for as little as $65.

Manufacturers built about 700 million smartphones last year. But the market has taken on a barbell shape. On one side are familiar names like Apple and Samsung, selling pricey phones for $300 to $600; on the other, several hundred lesser-known Chinese brands supplied by a thousand or more small factories.

The change began in 2011, when computer-chip makers began selling off-the-shelf chipsets—the set of processors that are the brains of touch-screen phones. Those, plus Google's free Android operating system, made smartphones much easier to produce.

The flood of inexpensive devices could force everyone to lower prices, including Samsung and Apple. "They have reached their peak," Liang said during an interview near his office in Shenzhen, which has become a hub for electronics makers. "In [manufacturing] technique we are close to the same level. Then the only difference will be the cost and the brand."

Larger Chinese companies, like Lenovo and Huawei, have also swarmed into China's market with midrange phones that cost closer to $200. Lenovo captured 12 percent of China's market last year.

Liang's phones are the ultracheap kind. He builds them at several Shenzhen factories, like Shenzhen Guo Wei Global Electronics, which opened in 1991 as a manufacturer of fixed-line phones and audio equipment. At Guo Wei, young Xunrui engineers lounge about, smoking cigarettes and drinking warm Coca-Cola while playing games on various brands of laptops.

One floor up, past a metal detector and an enclosure where high-pressured air blows dust and other impurities off workers' blue smocks, are the production lines—five of them, each with 35 young workers able to solder together and box up 3,000 smartphones a day.

Guo Wei has had to make some investments to get into the smartphone game, including importing new solder inspection equipment from Korea. One production line costs around $1.6 million to set up, according to Li Li, a production manager at the factory who showed off the equipment.

"The techniques are very complicated compared to older phones," says Li, who joined the factory 17 years ago to work in a department that repaired fixed-line telephones.

But the real reason for the switchover to smartphones was that last year large chip makers, including the Taiwan-based MediaTek and Spreadtrum, started offering "turn-key" systems: phone designs plus a set of chips with Android and other software preloaded. Spreadtrum says it may sell 100 million units this year.

$65

Retail cost of a basic smartphone in China

Each chipset costs $5 to $10, depending on the size of a phone's screen and other features. In total, Liang says, his cost to make a smartphone is about $40. He says that at Guo Wei and his other factories, he can manufacture as many as 30,000 smartphones a day for brands such as Konka Mobile and for telecom operators like China Unicom.

In the United States, a smartphone's high cost is generally masked by wireless companies, which discount them steeply if consumers agree to a contract. In China that happens as well. Liang says his phones retail for about $65 or $70 but can cost only $35 with a contract.

That is making China, now the world's largest smartphone market, a challenging place for foreign firms to compete. Apple accounts for 38 percent of U.S. smartphone sales, but its share in China is 11 percent and falling. Google has even bigger problems making money. Even though the devices use Android, they often don't come with Google's apps and search tool installed.

Liang says his aim is to make smartphones that are affordable, even if they aren't yet as good as an iPhone. That means the camera and LCD screen might not be the best, and the battery life could be shorter. "I always use this word 'acceptable,'" he says. "A lot of users only need an acceptable product. They don't need a perfect product."

What's certain, Liang says, is that the quality of the phones his factories produce will rise. "There is no profit at the bottom," he says. "Everyone is trying to improve their techniques." *—Michael Standaert with reporting by Su Dongxia*

SHOUT

Case Studies

How Facebook Slew the Mobile Monster

The fortunes of the world's largest social network depend on how much it can earn from mobile advertisements.

● Scarcely a year ago, Facebook was the poster child for Internet companies blindsided by the rapid shift of online activity from computers to smartphones and tablets. Just before its highly anticipated initial public offering in May, Facebook revealed that it wasn't making "any significant revenue" from its mobile website or app—even though more than half its 900 million members used the service on mobile devices.

By August, the widening gap between mobile usage and revenue had helped send shares plunging to under half their $38 offering price. The company had made "a bunch of missteps" in mobile, CEO Mark Zuckerberg sheepishly admitted in September.

Behind the scenes, though, Facebook was already finding its footing. From near zero last May, revenue from ads on mobile devices rocketed to $305 million in the last three months of 2012. That figure amounted to 23 percent of overall ad sales and helped lift shares back above $30 in January. "We are a mobile-first advertising company now," says Gokul Rajaram, Facebook's product director for ads.

That remains debatable, but Facebook's experience provides a lesson for anyone trying to cope with the mass migration of computer users to mobile phones and tablets. What Facebook discovered is that integrating ads directly into a user's flow of natural activities—in Facebook's case, the main feed where people view updates from friends—works far better than banners and pop-up ads. While these so-called native ads might be controversial, they look like advertising's most successful adaptation yet to mobile computing.

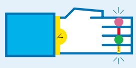
A year ago, Facebook faced all the usual problems: small screens, fewer technologies to target potential customers, and gaps in marketers' ability to measure the impact of mobile ads. These factors made ads look far less effective on mobile devices, and marketers less willing to pay for them.

Facebook's advertising team was also too preoccupied with pushing a new kind of desktop Web ad, called Sponsored Stories, to pay much attention to mobile. These ads are actions by a Facebook member, such as "liking" a page or checking in at a store, that marketers can then promote, for a fee, to the member's friends. Zuckerberg viewed these ads as the future of Facebook advertising because real posts from friends were less likely to be ignored.

By early 2012, Facebook was ready to start running them not just in the right-hand section reserved for ads but also on its prime real estate: the news feed, where people spend most of their time on the social network. Executives knew it was a risky step—especially when they extended the same type of ads to mobile as well. What if the ads really annoyed people?

Close to $0

Facebook's mobile advertising revenue during the first three months of 2012



$305 million

Facebook's mobile advertising revenue during the last three months of 2012

Far from it. Sponsored Stories got more clicks. But it was the mobile versions that really took off. They got twice as many clicks and commanded nearly three times as much from advertisers as those on the desktop, according to a subsequent study by advertising agency TBG Digital. By July, the mobile ads were grossing $500,000 a day.

Emboldened, Facebook launched other mobile ads over the summer and fall, including one that allowed makers of mobile apps to urge users to install their games or programs. This was an even bigger leap: it was the first ad in the mobile news feed that didn't require advertisers to wait for a "like" or other social action to create it. Advertisers instead could use Facebook's trove of biographical data from user profiles to target likely prospects, as they're accustomed to doing with traditional ads.

That worked, too. In January, for instance, Cie Games used app installation ads to draw players for its first iPhone game, Car Town Streets. The cost of acquiring them was 40 percent lower using Facebook's ads than using those from other mobile ad networks, says CEO Dennis Suggs. Even big brands are getting interested. During Thanksgiving weekend, Walmart bought 50 million mobile ads from Facebook, rivaling the reach of TV campaigns.

Facebook's success has exploded some myths of mobile marketing. Advertisers often complain that they can't run big, flashy ads on tiny screens. But Facebook's mobile ads take up a larger part of the screen than desktop ads do—one reason they get so many clicks. "Our ads are big and flashy," says David Fischer, Facebook's vice president of advertising and global operations. And they're getting more so: some mobile ads now include photographs, and Facebook is actively looking at incorporating video into them.

Everyone, including Zuckerberg, worried that users might balk at ads mixed with posts from friends. So far, that hasn't happened. Tests found that ads reduced comments, likes, and other interaction with posts by 2 percent, a decline that the company deems acceptable.

For all that, Facebook is still far behind the mobile-ad revenue leader, Google—which earned $2.2 billion from mobile search and ads in 2012. And as much as mobile ad revenues grew in the fourth quarter, some analysts fretted that growth wasn't even better, especially since mobile ads could be supplanting desktop ads.

Jacking up mobile ads even more, though, could be a challenge. Says TBG Digital CEO Simon Mansell, "They have to be careful they don't fill people's feeds with crap." —*Robert D. Hof*

Leaders

An Anti-iPad for India

Suneet Singh Tuli, the man behind the ultracheap Aakash 2 tablet, says the West doesn't understand mobile business in the developing world.

● A devout Sikh, Suneet Singh Tuli, 44, has found his own way to live by his religion's central belief of *sarbat da bhala*, or "may everyone be blessed."

He wants everyone in India to be on the Internet.

To that end, Tuli's London company, DataWind, is building inexpensive tablet computers, which it assembles in China or with the help of support staff at its India offices. The idea, Tuli says, is to pair cheap tablets with ad-supported wireless service as a way to bridge the digital divide between poor and rich countries.

DataWind began winning attention last year when it struck a deal to supply India's government with 100,000 of its Aakash 2 tablets, for roughly $40 each, by this March 31. That tablet works only near Wi-Fi points, but DataWind also sells an $83 commercial version called Ubislate 7C+, which comes with an unlimited mobile data plan for $2 per month. Within 18 months, Tuli says, he hopes to bring the price of a basic tablet down to $25 and make the Internet connection free.

Tuli's company is not a charity. DataWind plans to make money with its own app store and by displaying ads in its built-in browser (which also compresses websites for fast delivery over India's slow wireless networks). *MIT Technology Review* spoke with Tuli about his company's business model and the future of tablet computing in India.

"Hardware has gotten cheap enough that restaurants or resorts should be giving customers tablets to walk away with for free."

—Suneet Singh Tuli

You've said you never intended to be in the hardware business. What do you mean?

We think that hardware is dead. A gigahertz processor costs $4. It's good enough for most everything you'd want to do with a tablet, and not just for poor people in India. Hardware has gotten cheap enough that restaurants or resorts should be giving customers tablets to walk away with for free. Hardware is becoming a customer-acquisition tool.

So tablets should be literally disposable, like USB flash drives?

I don't like the word "disposable," but by 2015, you're going to see tablets reach the stage where you can just pick one up at 7-Eleven. And for consumers in the developing world, tablets will be their first computer.

We did a study to understand where the inflection point for PC deployment in the U.S. was: when did PCs really take off? Our assessment was that when the cost of purchasing PCs fell to within 20 percent of monthly salary, you started to see them in every home. In a place like India, there are about billion people for whom $50 meets that criterion.

What new businesses will ultracheap tablets lead to in the developing world?

There are going to be applications that will create billion-dollar opportunities, but we may not understand them in the West or be able to relate to them. My epiphany came when I saw a magazine ad in India that showed a minivan with a driver's seat that could be laid down 180 degrees. I thought, "How dumb is that?" Then I realized that most of these minivans were used as taxis, and the taxi drivers actually slept in them.

In the same way, the applications of these tablets will be very unique, and I'm not sure that I can comprehend what all of them would be. But I'm hoping that if we own the platform, we can become the conduit for those applications and those businesses.

You're practically giving away the tablets. So what's your strategy for making this into a business?

The first killer app on these devices is going to be Internet access. We have 18 patents on how to deliver basic Web access, even on India's GPRS networks. The idea is to bundle free Internet access with advertising on an affordable tablet. Basic browsing without audio or video streaming would be available for free, and we'd have a banner ad that runs on the top, which pays for the cost of data service and makes us money.

Does the Ubislate come with free Internet access right now?

In India, the free usage model is not in place yet. We have a Rs.98 ($1.80)-per-month data plan for unlimited usage. It is a fraction of what other plans cost, and we intend to drive it down to free.

What new opportunities do you see for apps in the developing world?

Nobody focuses on the problem of creating apps for somebody whose monthly income is $200. Those people are not part of the computer age or the Internet age; most of them are not literate. So we run app competitions in India to try to get people thinking from that perspective. The winner of our last competition was a group of students who designed a commerce app for "fruit walas," the guys who run around with carts selling fruits and vegetables. These students created a graphically intuitive way of running a small vegetable business.

There are something like five million fruit walas in India, so if you had an app for them, there could be a lot of money to be made. *—John Pavlus*

Reviews

Climate Change: The Moral Choices

The effects of global warming will persist for hundreds of years. What are our responsibilities and duties today to help safeguard the distant future? That is the question ethicists are now asking.

By David Rotman

One of the defining characteristics of climate change is poorly appreciated by most people: the higher temperatures and other effects induced by increasing levels of carbon dioxide in the atmosphere will persist for a very long time. Scientists have long realized that carbon dioxide emitted during the burning of fossil fuels tends to linger in the atmosphere for extended periods, even for centuries. Over the last few years, researchers have calculated that some of the resulting changes to the earth's climate, including increased temperature, are more persistent still: even if emissions are abruptly ended and carbon dioxide levels gradually drop, the temperature will stubbornly remain elevated for a thousand years or more. The earth's thermostat is essentially being turned up and there are no readily foreseeable ways to turn it back down; even risky geoengineering schemes would at best offset the higher temperatures only temporarily.

It's a shocking realization, especially given how little progress has been made in slowing carbon dioxide emissions. But it is precisely the long-term nature of the problem that makes it so urgent for us to limit emissions as quickly and radically as possible. To have a decent chance of meeting the widely accepted international goal of keeping warming at or below 2 °C, emissions need to be cut substantially over the next few years. By 2050 they must be reduced by half or more from 2009 levels.

Climate Matters: Ethics in a Warming World
John Broome
W.W. Norton, 2012

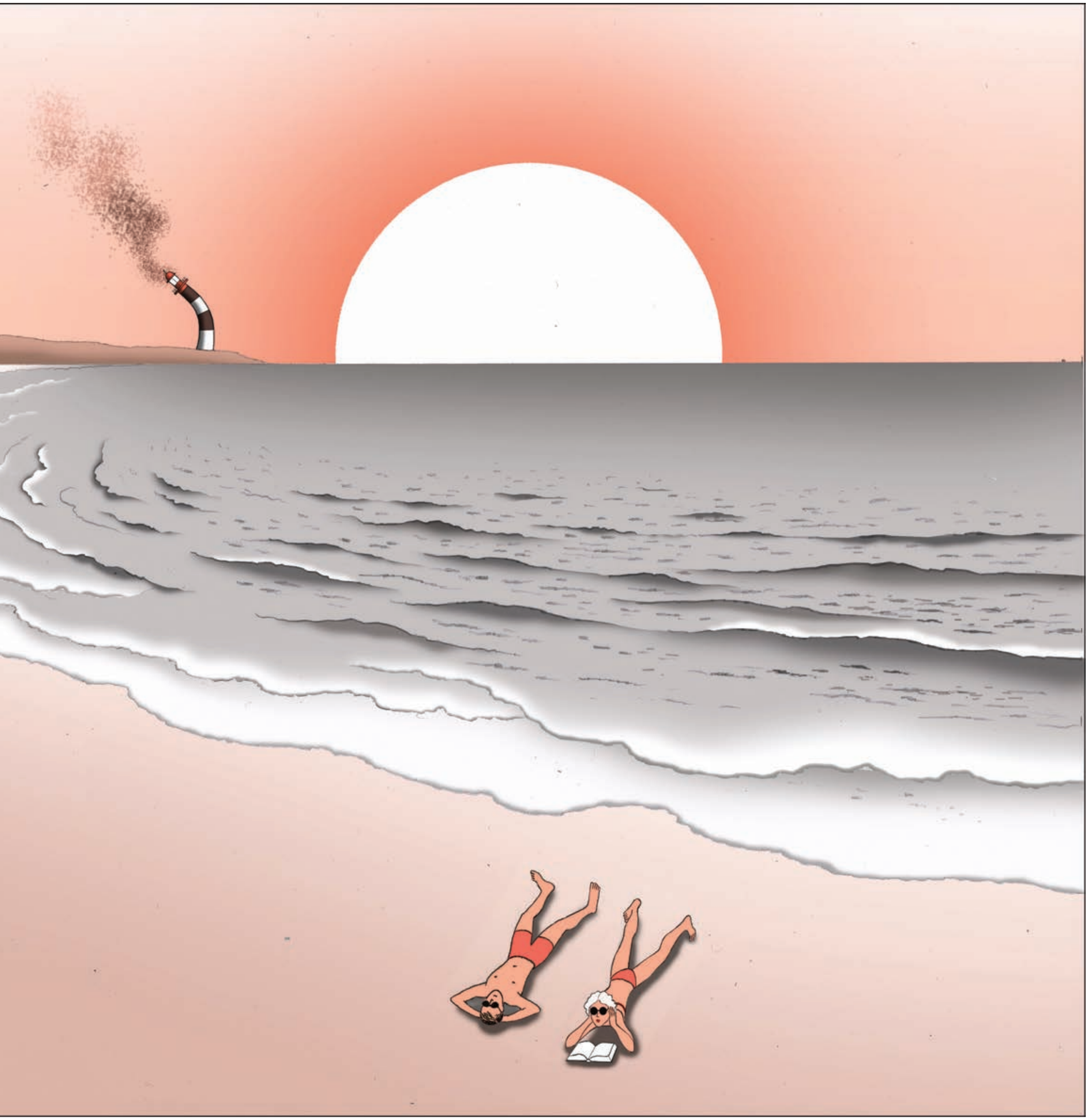
Earthmasters: The Dawn of the Age of Climate Engineering
Clive Hamilton
Yale University Press, 2013

A Perfect Moral Storm: The Ethical Tragedy of Climate Change
Stephen M. Gardiner
Oxford University Press, 2011

The mismatch between when we need to act and when many of the benefits will accrue helps to explain why climate change is such a politically and economically thorny problem. How do you convince people and governments to invest in a far-off future? Clearly, it is not a problem that can easily be addressed by most politicians, given the immediate and pressing needs of their constituents. Because it involves defining and understanding our responsibilities to future generations, our action (or inaction) on climate change falls squarely into the realm of moral and political philosophy.

Over the last few years a small but growing number of writers have begun to wrestle with some profound questions. What ethical guidelines should economists follow when evaluating today's costs against future benefits? How should we weigh uncertainties, including the risks of catastrophic changes wrought by global

GUY BILLOUT



warming? Would geoengineering be ethical? How does climate change affect our perception of the world and our future role in it? The conclusions they've reached are nuanced and can turn on esoteric definitions of terms such as "justice" and "moral good." But their reasoning often provides keen insights into today's most pressing policy questions.

Even if people are richer in the future, climate change might reduce the quality of their lives.

Future Value

In *Climate Matters: Ethics in a Warming World*, John Broome, a moral philosopher at the University of Oxford, explains the methods and arguments that help us understand the ethical implications of global warming, and he demonstrates why this reasoning can offer useful insights into how we should act. Trained in economics at MIT, Broome is particularly interested in assessing the ethical judgments made by economists. "Economists recognized, say, 50 years ago that economics is based on ethical assumptions," he says. "But a number of them seem to have forgotten that in recent decades. They think what they do is somehow in an 'ethic-free zone.' And that plainly isn't so. And climate change makes that obvious."

One of the most controversial issues in economic analysis of climate-change policy is how to weigh the cost of implementing changes now against the benefits that future generations will realize—or the harm they will avoid. It might be supposed that we should do everything we can possibly do now, but that would probably be wrong, suggests Broome, since extremely radical action would have such negative consequences for those alive today that the effects would be felt for generations. Broome wrestles with how to balance these factors in an ethically responsible way, concluding that economists are, in general, right in adopting so-called cost-benefit analyses to evaluate actions on climate change. But he stresses that the ethical assumptions underlying such analyses are critical—and that economists often ignore or misunderstand them.

A standard tool in cost-benefit analysis is what economists call the discount rate, which makes it possible to apply a value today to an investment that won't pay off until some future date. In Broome's example, if the discount rate is 6 percent per year, you could buy a given amount of rice now, but you should pay 94 percent of that price today if it were to be delivered in a year or 83.06 percent if it were to be delivered in three years. The basic idea is that people will be richer in the future as economies keep growing, so a given amount of a commodity or money will have less value than it has now. The higher the discount rate, the less value is assigned to a future commodity.

The way economists calculate discount rates has enormous implications for energy policy. In 2006, Nicholas Stern, a prominent economist at the London School of Economics and former chief economist of the World Bank, published "The Economics of Climate Change," an influential report that called for immediate and significant spending (he has more recently called for even larger investments; see our Q&A from May/June 2011). Stern used an unconventionally low discount rate of 1.4 percent, which led him to place a high value on the future benefits of today's investments to address climate change. He was immediately attacked by a number of academic economists. Most notably, William Nordhaus of Yale University published *A Question of Balance*, in which he argued that the appropriate discount rate should be about 5 percent. Nordhaus thus concluded that spending to deal with climate change should be much more gradual, and that much of it should be delayed for several decades.

Typically, economists calculate the discount rate by using money markets to determine the expected return on capital. The reasoning is that the market is the most democratic means of assigning value. But while that practice might work well to account for the value of commodities, Broome argues that calculating the discount rate for action on climate change is far more complex. For one thing, the conventional method doesn't fully account for the possibility that even if people are richer in the future, climate change might reduce the quality of their lives in other important ways—and thus it underestimates the value of current investments. Broome ends up supporting a rate similar to Stern's.

But his larger point is, more simply, that even such quantitative economic evaluations need to fully incorporate moral principles.

> The discount rate is a matter of the value of future people's benefits compared to our own. More than anything else, it determines what sacrifices the present generation should make for the sake of the future. This is a moral matter.

Broome also ponders the implications of how we think about extreme risk. Most people accept that it is worthwhile to invest in avoiding a particularly onerous outcome, even if it is not a likely one. That's why we buy fire extinguishers and home fire insurance, even though a fire is unlikely. But how should we value the ability to avoid a catastrophic outcome that is very improbable? Some leading economists have begun arguing that heading off even the remote chance of such outcomes should be the main object of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All-new stories by 12 of today's visionaries

climate-change policy. Not surprisingly, Broome calls for using moral principles to evaluate just how bad various outcomes could be and how much we should concentrate on avoiding them. That means making difficult decisions about the value of human lives and of natural systems; it also means calculating how "bad" it would be if climate change reduced the size of the human population. "Deciding whether it will be very, very bad takes ethical analysis," he says.

Broome's focus on the reasoning of economists is not arbitrary. Economists have "largely been in the driver's seat" in guiding governments' policies on climate change, he says. "But they don't always get their ethical foundations right." By not fully accounting for people's future well-being and such difficult-to-quantify values as the beauty of nature, Broome says, many economists have seriously underestimated how much we should be spending now to address climate change.

What Would God Do?

In his 2010 book, *Requiem for a Species: Why We Resist the Truth about Climate Change*, Clive Hamilton, a professor of public ethics at Charles Sturt University in Canberra, Australia, argues that it is already too late to stop many of the dire consequences of global warming and that we're almost sure to make it far, far worse.

After that book was published, Hamilton says, he became convinced that the "growing gap" between the widely accepted scientific evidence for the dangers of global warming and the lack of any political progress toward addressing the problem would increase the pressure to view geoengineering as a feasible option. He expects it to become "the dominant issue in climate-change discussions within the next five to 10 years." So in his newest book, *Earthmasters: The Dawn of the Age of Climate Engineering*, Hamilton takes a critical look at various geoengineering proposals, such as the use of sulfur particles or manmade materials to partially block the sun (see "A Cheap and Easy Plan to Stop Global Warming," March/April 2013). He is highly skeptical of any such schemes to rejigger the earth's atmosphere to fix climate change and deeply suspicious of the motivations of many of its advocates.

Hamilton uses the term "playing God" to describe the hubris of some of the people suggesting geoengineering. He doubts we would be very good at it, or very fair in applying a technology that would be likely to harm some people and help others. Perhaps most damning, he says that it raises moral problems—and strains common sense—to propose using such risky measures because we have failed to tackle climate change with existing technologies.

> If humans were sufficiently omniscient and omnipotent, would we, like God, use climate engineering methods benevolently? Earth system science cannot answer this question, but it hardly needs to, for we know the answer already. Given that humans are proposing to engineer the climate because of a cascade of institutional failings and self-interested behaviours, any suggestions that deployment of a solar shield would be done in a way that fulfilled the strongest principles of justice and compassion would lack credibility, to say the least.

In Hamilton's thinking, geoengineering is the latest example of our hope that "techno-fixes" will rescue us from global warming. He points to large—and, he says, largely fruitless—investments in carbon capture and storage (CCS) as a way to negate the emissions from burning coal and writes that the "false promise" of CCS has contributed to a "lost decade in responding to climate change." The problem is not only that such "energy miracles" are unlikely to work as advocates hope but that the prospect of them presents a moral hazard, tempting people to persist in risky actions without expecting dire consequences. What's more, says Hamilton, relying on techno-fixes ignores the underlying economic, political, and ethical failures that have produced the climate-change crisis in the first place.

We have barely begun to grapple with the moral issues related to climate change.

More broadly, Hamilton emphasizes the "astonishing ethical implications" of climate change over the long term—and of what would-be geoengineers are proposing. We're at "a historical point," he says. "We need to reopen the question of who we are as a species and what kind of a creature we have become." Yet the attentive reader will note that Hamilton doesn't rule out geoengineering in the future, if the situation becomes desperate. Rather, he calls on us to examine the economic and political motivations of geoengineering advocates and to understand that trying to engineer the climate reflects a misplaced faith in technology's ability to solve political and social problems.

In *A Perfect Moral Storm: The Ethical Tragedy of Climate Change*, Stephen M. Gardiner reaches similar conclusions after a far different type of analysis. Unlike Hamilton, Gardiner, a professor of philosophy at the University of Washington, has little interest in the players and politics behind geoengineering. Instead, he rigorously analyzes the moral justifications for considering the technology.

In particular, he questions the simplistic reasoning that since geoengineering could turn out to be the "lesser evil" in some future climate emergency, we should be researching it now to understand the technology and its risks. That argument

conceals many ethical challenges, he contends. Is it ethical of us to expect a future generation to take on the dangers and costs of geoengineering because we have failed to address climate change? And wouldn't a large research push on geoengineering just increase the unfortunate possibility that it will be used?

Crosswinds

Though they reflect very different interests and objectives, these books, taken together, begin to shed light on why climate change has been such a difficult problem to address and even define. After all, if it is fundamentally a moral issue, then simple economic or technology-based solutions will understandably fall short.

What's more, climate change poses particularly tough moral problems. The title of Gardiner's book refers to the convergence of three separate moral "storms," or "obstacles to our ability to behave ethically." The biggest is the way future generations are at the mercy of current ones —what he sometimes calls generational buck-passing. The others involve the different impacts of climate change around the world and among different populations, and the prospect that theoretical uncertainties in areas such as intergenerational ethics and climate science will make it difficult for us to act. Gardiner spends nearly 500 pages trying to map the crosswinds of these storms, concluding that "it will not be easy for us to emerge morally unscathed."

Still, a clear first step would be to acknowledge the moral issues associated with climate change and the likely need for some painful decisions. Gardiner rightly points out that much of the public debate is dominated by "technological and social optimists" who argue for "win-win" solutions that will allow us to address the problem without any economic sacrifices or hard ethical choices. Might green energy simply solve the problem, not only for us but for future generations? We're beginning to know the answer; a clean-tech revolution hasn't come close to happening, in part because it would necessarily mean making difficult choices. What's more, says Gardiner, clinging to that hope obscures the real reasons we need to do something about climate change:

> More generally, the current focus on the green energy revolution rationale puts pressure in the wrong place. The dominant reason for acting on climate change is not that it would make us better off. It is that not acting involves taking advantage of the poor, the future, and nature ... The green revolution claim runs the risk of obscuring what is at stake in climate change, and in a way that undercuts motivation. The key point is that we should act on climate change even if doing so does not make us better off: indeed, even if it may make us significantly worse off. If we hide or dilute the moral issues, then this important truth is lost, and the prospects for ethically defensible action diminish.

We have barely begun to grapple with the moral issues related to climate change. Indeed, few are even likely to accept the basic role that ethical issues should play in our policy decisions, and certainly our responsibilities to the distant future are seldom part of the public debate. But given the convincing evidence climate scientists have presented that our actions over the next several decades will have direct consequences for generations who will live many years from now, we must consider the moral dimensions of our response. As Gardiner puts it at the end of his book: "The time to think seriously about the future of humanity is upon us." T

David Rotman is the editor of MIT Technology Review.

BOB STAAKE

2013 Ford Fusion with Adaptive Cruise Control and Lane-Keeping System

2010 Lincoln MKS with Active Park Assist

The Design of Future Things
Don Norman
Basic Books, 2007

"Monitoring, Managing, and Motivating Driver Safety and Well-Being"
Joseph F. Coughlin, Bryan Reimer, and Bruce Mehler
IEEE Pervasive Computing, July–September 2011

Proceed with Caution toward the Self-Driving Car

Completely autonomous vehicles will remain a fantasy for years. Until they're here, we need technology that enhances human drivers' abilities rather than making those abilities increasingly obsolete.

By Will Knight

Driving on Interstate 495 toward Boston in a Ford Fusion one chilly afternoon in March, I did something that would've made even my laid-back long-ago driving instructor spit his coffee over the dashboard: I took my hands off the steering wheel, lifted my foot off the gas pedal, and waited to see what would happen. The answer: not much. To a degree, the car was already driving itself. Sensors were busy tracking other vehicles and road markings; computer systems were operating the accelerator, the brake, and even the steering wheel. The car reduced its speed to keep a safe distance from the vehicle ahead, but as that car sped up again, mine did so too. I tried nudging the steering wheel so that we drifted toward the dotted line on my left. As the line approached, the car pushed the steering wheel in the opposite direction very slightly to keep within its lane.

The technology behind this kind of vehicle automation is being developed at a blistering pace, and it should make driving safer, more fuel-efficient, and less tiring. But despite such progress and the attention surrounding Google's "self-driving" cars, full autonomy remains a distant destination. A truly autonomous car, one capable of dealing with any real-world situation, would require much smarter artificial intelligence than Google or anyone else has developed. The problem is that until the moment our cars can completely take over, we will need automotive technologies to strike a tricky balance: they will have to extend our abilities without doing too much for the driver.

Carmakers have so far introduced autonomous technology carefully, aware that having too little to worry about behind the wheel can be just as dangerous as having too many distractions. I

could detect the automakers' restraint when I drove on I-495 in the Ford Fusion, a $30,000 sedan that has two partly autonomous systems: Adaptive Cruise Control, which uses radar to measure the distance to the car in front and controls the accelerator and brake to maintain a safe distance; and the Lane-Keeping System, which uses a camera in the rear-view mirror to monitor lane markings and vibrates the steering wheel, or gently moves it, if the car drifts too far to the left or right. The capabilities of both are clearly held in check. The cruise control system doesn't work below 12 miles per hour and shuts off if the car ahead starts going faster than the initial set speed; the lane-tracking feature can easily be overridden by moving the steering wheel forcefully. It also switched off a couple of times when the stripes on the road were too worn to be seen clearly. But even with such limitations, these two systems are remarkably clever and reassuring to use. Driving home in another car later, I felt hamstrung not seeing my position within the lane shown clearly on the dashboard.

When implemented correctly, automation quickly feels like just a natural part of driving. In fact, it's easy to forget that it has been creeping into cars ever since the hand crank was replaced by an automatic starter in 1911. But this progression is accelerating with systems that perform much higher-level driving tasks. Numerous carmakers sell models that apply the brakes at superhuman speed if they detect an impending collision; some can help read road signs as they whiz past, and then remind the driver of the correct speed limit.

Many cars can also perform one of the most troublesome driving tasks, parallel parking. I tried this feature, called Active Park Assist, in a Lincoln MKS. The system identifies a suitable spot and then executes a near-perfect reversing maneuver while the driver operates the brake. It was unnerving, at first, to see the steering wheel spin violently as the car backed into an empty spot, but I also marveled at how flawlessly it worked.

This experience also hinted at the biggest challenge for increased vehicle automation: how to merge human and machine abilities effectively. Bryan Reimer, a research scientist at MIT's Age Lab, who uses the Lincoln to study driver behavior, was sitting in the passenger seat during my test drive as I searched for a parking spot. He warned me not to accept the first few that the car offered to squeeze into, not because he doubted the technology but because he doubted my ability to undo what it did. "You'll just never get out of there," he said, pointing out that the Lincoln can park itself with just a few inches to spare on either end.

Cars with autonomy still require a human's attention, but they can also discourage it.

How to make sure autonomy meshes with human behavior is a topic that Don Norman, a cognitive scientist and product design consultant, explores in depth in his 2007 book *The Design of Future Things*. Norman foresees many potential problems with more autonomous cars; in fact, he points out, some have already cropped up. He describes how he worked with automakers whose adaptive cruise control systems would automatically speed a car up as a driver entered an off-ramp, because the ramp was free of traffic; or they would suddenly slow a car down if the driver pulled in close behind another car while changing lanes, thereby forcing the car behind to brake suddenly as well. "Fully automatic control will be safer," he writes. "The difficulty lies in the transition toward full automation, when only some things will be automated."

It's tempting to think the problems Norman identifies will be short-lived. After all, Google has been testing a fleet of almost completely autonomous, or "self-driving," hybrid cars for some time. These vehicles use an expensive laser mounted on the roof to map the car's surroundings in 3-D and rapidly process this picture, reacting deftly to other cars and pedestrians. The company says its cars have traveled more than 300,000 miles without a single accident while under computer control. Last year it produced a video in which a blind man takes a trip behind the wheel of one of these cars, stopping at a Taco Bell and a dry cleaner.

Impressive and touching as this demonstration is, it is also deceptive. Google's cars follow a route that has already been driven at least once by a human, and a driver always sits behind the wheel, or in the passenger seat, in case of mishap. This isn't purely to reassure pedestrians and other motorists. No system can yet match a human driver's ability to respond to the unexpected, and sudden failure could be catastrophic at high speed.

But if autonomy requires constant supervision, it can also discourage it. Back in his office, Reimer showed me a chart that illustrates the relationship between a driver's performance and the number of things he or she is doing. Unsurprisingly, at one end of the chart, performance drops dramatically as distraction increases. At the other end, however, where there is too little to keep the driver engaged, performance drops as well. Someone who is daydreaming while the car drives itself will be unprepared to take control when necessary.

Reimer also worries that relying too much on autonomy could cause drivers' skills to atrophy. A parallel can be found in airplanes, where increasing reliance on autopilot technology over the past few decades has been blamed for reducing pilots' manual flying abilities. A 2011 draft report commissioned by the Federal Aviation Administration suggested that overreliance on automation may have contributed to several recent crashes involving pilot error. Reimer thinks the same could happen to drivers. "Highly automated driving will reduce the actual

Google's demonstration is deceptive. Nothing can yet match a human driver at handling the unexpected.

physical miles driven, and a driver who loses half the miles driven is not going to be the same driver afterward," he says. "By and large we're forgetting about an important problem: how do you connect the human brain to this technology?"

Norman argues that autonomy also needs to be more attuned to how the driver is feeling. "As machines start to take over more and more, they need to be socialized; they need to improve the way they communicate and interact," he writes. Reimer and colleagues at MIT have shown how this might be achieved, with a system that estimates a driver's mental workload and attentiveness by using sensors on the dashboard to measure heart rate, skin conductance, and eye movement. This setup would inform a kind of adaptive automation: the car would make more or less use of its autonomous features depending on the driver's level of distraction or engagement.

Already, some systems watch for behavioral cues that the driver's focus is wandering. Indeed, after I had been cruising along I-495 for a few moments under the car's control, this message flashed on the dashboard: "Driver Alert Warning: Put Hands Back on Steering Wheel." For the rest of my drive, I made sure I did.

Will Knight is MIT Technology Review's *online editor.*

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45 Years Ago

Can IT Cure Congress?

In 1968, an instructor of political science had reason to hope that computers would make government wiser.

"**Computer-based analysis as it is refined over the** remaining decades of this century will make possible an advance in human intellectual capacity comparable to the invention of language, Arabic numerals, and calculus. With his new ability to understand the dynamics of complex organizations and social processes, the congressman of tomorrow will explore a range of problems previously beyond the grasp of his predecessors.

Studies by RAND Corporation experts suggest that by the early 1970s computers will be small, powerful, plentiful, and inexpensive. Computing power will be available to anyone who needs it, or wants it, or can use it either by means of a personal console connected to some large central facility, or by a small personal machine ... By the mid-1980s, the computer will begin to realize its potential as a research tool through modeling and experimentation, as an integral part of the educational system, and in areas such as medicine and biological sciences ...

One can readily foresee a congressman sitting at a console in his office poring over computer print-outs into the late evening hours or over the weekend and cutting through the paper arguments and justifications of executive programs with penetrating lines of questions. The possibility of abuse also exists, but the weight of past congressional experience suggests that most congressmen will use such new investigative power wisely. In situations that invite adversary argument, alternative positions and points of view will be more thoroughly developed and cogently presented.

The analytical concepts and techniques associated with the new information technology—systems analysis, program budgeting—are not particularly new. What is new is the capacity of automatic data processing to make 'operational' the concept of an organization as a total system. The revolution in information technology represents an almost immeasurable potential increase in man's knowledge—especially in his understanding of and ability to control his environment. The intelligent use of that knowledge and the power it confers is an awesome responsibility. In a political democracy it involves the democratic consideration of emerging technological possibility and consequence. The multiple perspectives of the American system, the numerous points of access for developing, testing, and advancing ideas may ultimately prove to be among the greatest assets of American democracy in the future."

Excerpted from "System Politics: The Presidency and Congress in the Future," by John S. Saloma, associate professor of political science at MIT, in the December 1968 issue of Technology Review.

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